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THE FLIGHT DYNAMICS LABORATORY (FDL) IS ONE OF THE WORLD'S MOST ADVANCED AIRCRAFT TECHNOLOGY DEVELOPMENT FACILITIES. THIS REPORT EXAMINES THE PAST, PRESENT AND FUTURE OF THE FLIGHT DYNAMICS LABORATORY ACCORDING TO FIVE BROAD TECHNOLOGICAL AREAS: FLIGHT CONTROL, VEHICLE EQUIPMENT OR SUBSYSTEMS, AEROMECHANICS, STRUCTURES, AND DYNAMICS. ADVANCED DEVELOPMENT PROGRAMS CLOSELY IDENTIFIED WITH A PARTICULAR DIVISION ARE INCLUDED IN THE APPROPRIATE CHAPTER, WHILE OPERATIONAL AND TECHNICAL SUPPORT ARE COVERED IN A SEPARATE SECTION.

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OCTOBER, 1988

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FLIGHT DYNAMICS LABORATORY
AIR FORCE WRIGHT AERONAUTICAL LABORATORIES
AIR FORCE SYSTEMS COMMAND
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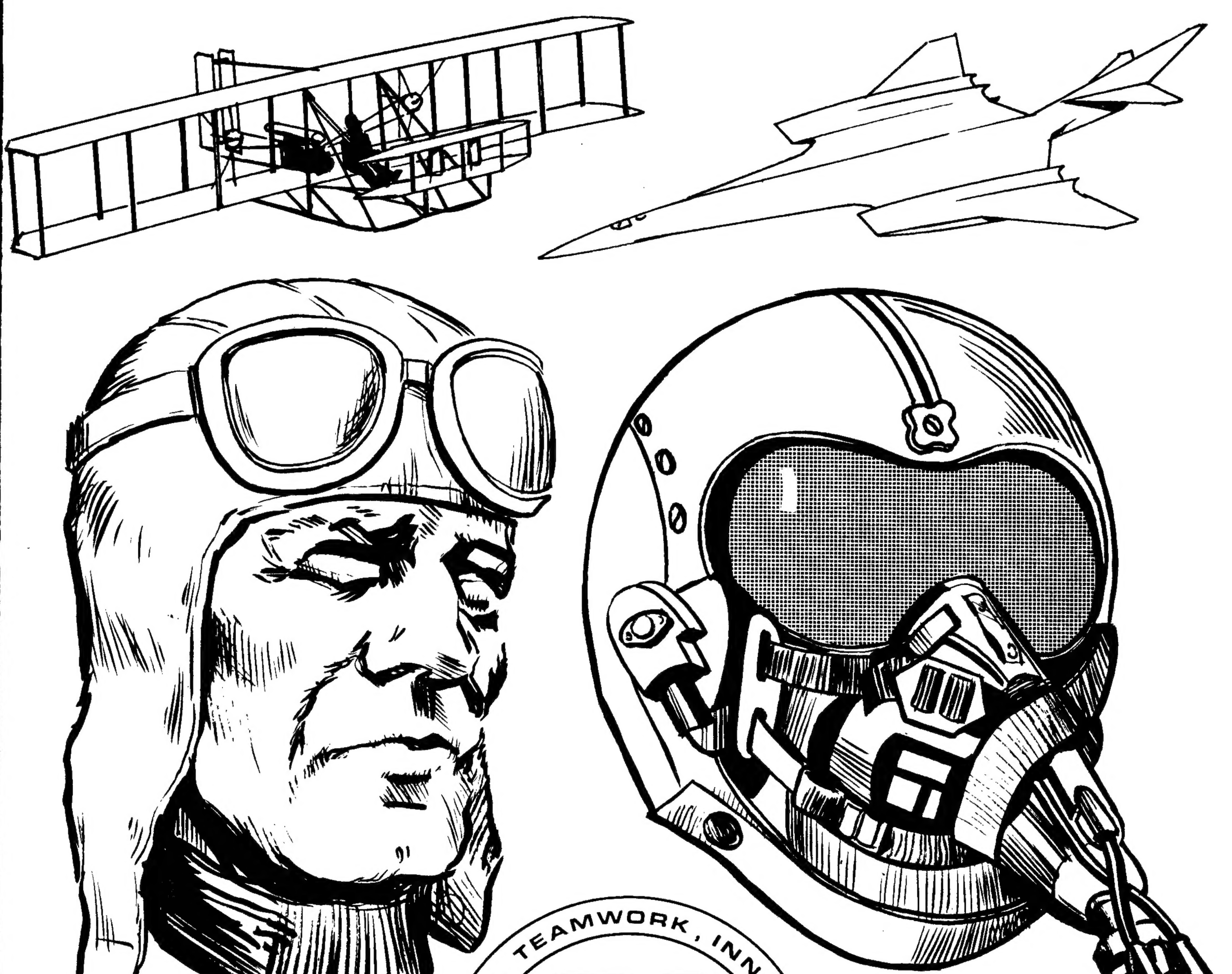
THE HERITAGE OF THE FLIGHT DYNAMICS LABORATORY



QUALITY, TEAMWORK, INNOVATION
FLIGHT DYNAMICS LABORATORY
FDL MAKING A DIFFERENCE

The Flight Dynamics Laboratory:

Evolution of an Engineering Miracle

October 1988

Foreword

The Flight Dynamics Laboratory (FDL), one of the world's most advanced aircraft technology development facilities, was created in April 1963. The Laboratory plans, formulates and executes USAF basic research, exploratory and advanced development programs for aerospace flight vehicle structures and dynamics, vehicle equipment and subsystems, flight control, aeromechanics and flight vehicle technology integration, simulation and demonstration. In addition it performs a continuing assessment of these assigned technologies and their interaction with other technologies to enhance technology development, integration and transition, and performs as a focal point for non-nuclear survivability research and development. The Lab also provides technical and management support of aerospace systems, is lead laboratory for experimental flight vehicles, crew systems integration, and assigned Air Force Wright Aeronautical Laboratories major thrusts. FDL maintains pre-eminent technical and scientific leadership in military aerospace vehicle technologies. This leadership has been recognized many times by industry and the military; the Lab and individual employees have received a great many tributes, including the prestigious Foulois Award. From futuristic research vehicles like the X-29 to parachutes and fire extinguishers, the Flight Dynamics Lab and its predecessors have led the world in advanced aircraft technology for more than sixty years.

The number of factors impacting on the development of any new technology or weapon system can approach the astronomical. By concentrating on the role of the Flight Dynamics Lab, we do not intend to downgrade the contributions of academia and nonprofit research establishments, of industry, or of other military organizations. FDL could not function without a beneficial relationship with its sister laboratories and with the National Aeronautic and Space Administration, the Arnold Engineering Development Center, and other facilities. In these pages the question of funding also receives less attention than it deserves. The procurement process can be long and complex, and has a fundamental influence on the direction taken by research and development in every government lab. The Military Construction Program is responsible for providing the research facilities required by these labs, and its influence must also be acknowledged.

This report examines the past, present and future of the Flight Dynamics Laboratory according to five broad technological areas: flight control, vehicle equipment or subsystems, aeromechanics, structures, and dynamics. Advanced development programs closely identified with a particular division are included in the appropriate chapter, while operational and technical support are covered in a separate section. A final chapter takes a look at some of the more broad-spectrum advanced development programs. Major technical terms are defined in the text, while minor or more general terms can be found in the glossary. We will begin with the history of the Laboratory's organizational predecessors.

A visitor to the Lab is often impressed by the complex array of test rigs, computers and simulators scattered through dozens of buildings at Wright-Patterson Air Force Base. But the key to the FDL's success is its people. Many present and former employees, civilian and military, have been interviewed in the course of the FDL Heritage Project, and their insights and memories have been essential. This book is for them.

A Flight Dynamics Lab Chronology

August 1907

The Aeronautical Division was established by the US Army Signal Corps.

February 1908

The Aeronautical Division contracted with the Wright Brothers for the Army's first airplane. It crashed before it was delivered.

August 1909

The Aeronautical Division took delivery of its first Wright Flyer, Model "A."

March 1911

For the first time, Congress appropriated funds specifically for aeronautical research and development.

July 1914

World War I began in Europe. Congress created an Aviation Section within the Signal Corps.

1915

The National Advisory Committee for Aeronautics (NACA) was established.

April 1917

The United States entered World War I.

1917

The Airplane Engineering Department -- first ancestor of today's Flight Dynamics Lab -- was established; in September the Signal Corps acquired McCook Field, which opened in December.

May 1918

The Army Air Service was created, transferring responsibility for aeronautical development away from the Signal Corps. In August the Airplane Engineering Department became a division of the AAS.

November 1918

World War I ended.

January 1919

The Airplane Engineering Division was renamed the Technical Division, which was responsible for airframes, armaments, engines, equipment, and materials.

March 1919

The Technical Division became the Engineering Division, under whose aegis many of the remarkable advances of the 1920s were made at McCook Field.

August 1924

The small Wilbur Wright Field, east of Dayton, was expanded, and the Air Service began preparations to move the Engineering Division there.

October 1926

The Army Air Corps was established, with a Material Division headquartered at McCook Field.

1927

Throughout the year, the McCook facilities were gradually moved to Wright Field. The new buildings were dedicated in October.

1939

The Airplane Lab was reorganized as the Aircraft Laboratory; Material Division was moved to Washington, D.C.

September 1939

World War II began in Europe.

June 1941

The War Department established the Army Air Forces.

December 1941

The United States entered World War II.

March 1942

The Materiel Division became a command, and thirteen months later moved its headquarters from Washington to Wright Field.

1944

The Air Technical Service Command was created to include the engineering and production functions of the Materiel Command and the supply and maintenance responsibilities of the Air Service Command.

September 1945

World War II ended.

March 1946

The Air Technical Service Command became the Air Materiel Command as part of a complete reorganization of the Army Air Corps.

September 1947

The United States Air Force was created.

January 1950

Recognizing the crucial importance of aeronautical research and development, the Air Force appointed a Deputy Chief of Staff for Development and established the Air Research and Development Command.

April 1951

Four separate units -- the Engineering Division, the Flight Test Division, the All-Weather Flying Division, and the Office of Air Research -- were provisionally combined as the Air Development Force. Soon, these elements were assigned to the Air Research and Development Command, under the name Wright Air Development Center.

1954

The Flight Control Laboratory was organized within WADC.

December 1959

WADC became the Wright Air Development Division (WADD).

April 1961

WADD was discontinued, its laboratories being organized as part of the Aeronautical Systems Division under the Air Force Systems Command.

March 1963

ASD/Directorate of Aeromechanics was reorganized with two new elements: the Air Force Flight Dynamics Laboratory and the Air Force Aero Propulsion Laboratory. Today's FDL comes into being.

July 1963

Operational control of AFFDL was transferred to Research and Technology Division (RTD), but administrative control was retained by ASD.

August 1963

AFFDL was assigned to the Research and Technology Division.

November 1963

AFFDL was assigned to the Air Force Systems Command.

July 1975

The Air Force Wright Aeronautical Laboratories (AFWAL) was established by AFSC to direct the Air Force Laboratories at Wright-Patterson, including AFFDL, Avionics, Materials, and Propulsion.

January 1980

AFFDL was formally inactivated, its functions continuing under AFWAL as the Flight Dynamics Laboratory.

November 1982

AFWAL was reassigned to the Aeronautical Systems Division.

October 1988

AFWAL was reorganized and renamed the Wright Research and Development Center under ASD. The Flight Dynamics Laboratory continued as before but some units were assigned to new WRDC directorates.

Air Force Flight Dynamics Laboratory Commanders

Col. William C. Nielsen
October 1963 - July 1964

Col. George T. Buck
July 1964 - June 1967

Col. Dale O. Davis
June 1967 - May 1968

Col. Joseph R. Myers
July 1968 - February 1971

Col. Charles A. Scolatti
February 1971 - May 1974

Col. Brien D. Ward
May 1974 - June 1975

Air Force Flight Dynamics Laboratory Commanders

Col. Albert E. Preyss
July 1975 - July 1977

Col. George F. Cudahy
July 1977 - September 1979

Col. Robert C. Barlow
November 1979 - June 1983

Col. Larry G. Van Pelt
January 1984 - July 1985

Col. Thaddeus H. Sandford
January 1986 - January 1989

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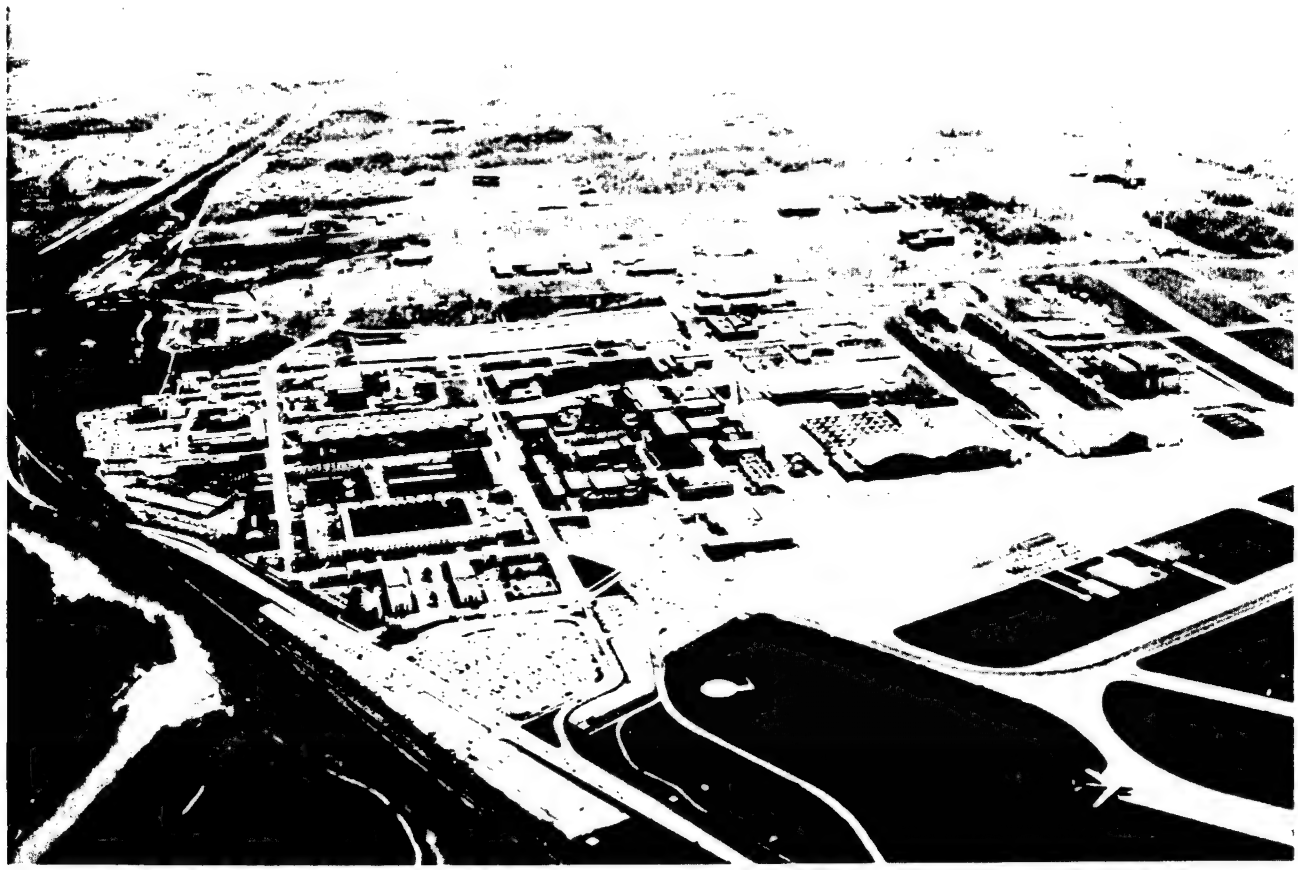
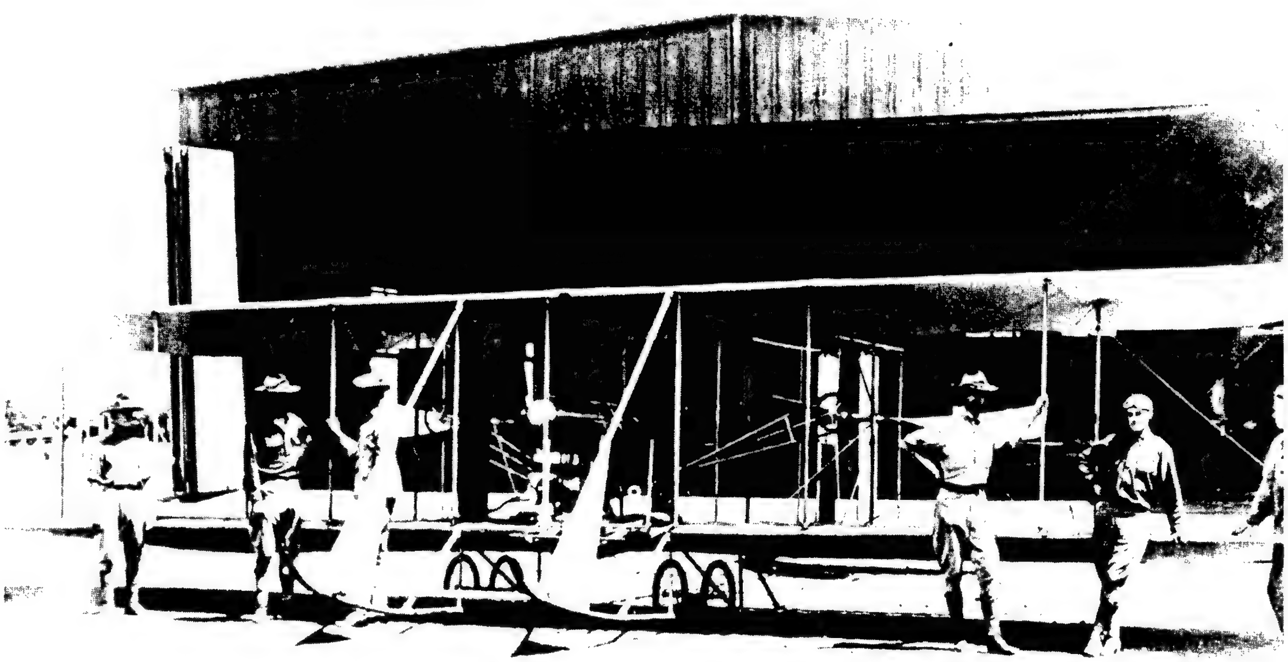


Aerial View of Wright-Patterson Air Force Base, Area B -- home of the Flight Dynamics Laboratory.

The Early Years

The roots of the Flight Dynamics Laboratory run deep in the history of American aviation. Few units of today's Air Force have so long a history, and fewer still have contributed so much to aeronautical research and development. The predecessors of the FDL antedate all other Air Force research facilities and have originated countless new technologies. It is not an exaggeration to say that modern aviation is what it is largely because of the Flight Dynamics Lab.

In August 1907 the Army Signal Corps, which had long used balloons for reconnaissance, was given responsibility for the military development of "air machines." A year later three Signal Corps lieutenants began training as dirigible pilots, and in the autumn of 1909 two of these men and a third recruit learned to fly "Signal Corps Airplane Number One," a Wright Flyer. In 1910 two of the lieutenants were reassigned, leaving Benjamin D. Foulois as the Army's only pilot. He took the Wright plane to Fort Sam Houston, Texas, and kept it in good repair -- sometimes using his own money -- until 1911. In that year five more aircraft were purchased for what was by then called the Aeronautical Division.

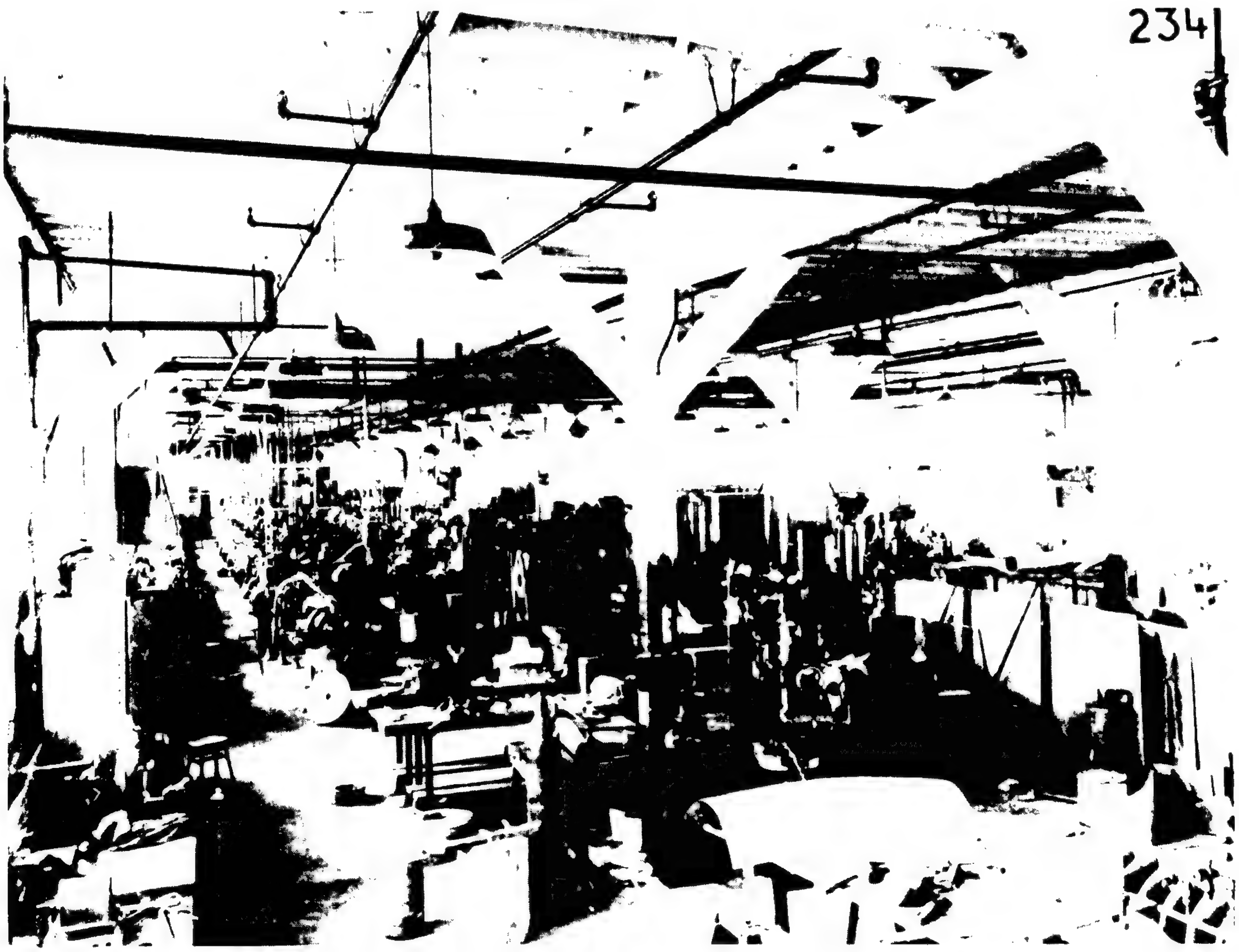


Lt. Benjamin D. Foulois (second from right) with Wright "B" Flyer (1910).

By the time World War I broke out in Europe the renamed Aviation Section was still minuscule, and there was no engineering experimentation under way -- the European powers were far ahead of the United States in all aspects of aeronautical research. However, the Army did establish a pilot training school at San Diego, and by the time the United States entered the war in April 1917, the Army owned one hundred and thirty-two aircraft.

The Aviation Section quickly recognized the need to catch up with Europe in the aircraft engineering field. At its recommendation Congress, in March 1915, established the National Advisory Committee for Aeronautics (NACA) to conduct research and experimentation "in any laboratory, in whole or in part, which may be assigned to it." Plans were made to establish such laboratories in Dayton and at Hampton, Virginia (Langley Field).

On 24 May 1917 the Army established the Aircraft Engineering Division to conduct research on the improvement of aircraft design. This unit was a forerunner of today's Flight Dynamics Laboratory. In July Congress passed an appropriations bill, granting an astonishing $640 million for military aviation. Aircraft research suddenly mushroomed. On 15 August, the Aircraft Engineering Division was divided into the Plane Design Section and the Engine Design Section: the first was a forerunner of today's FDL, the second eventually emerged as the Aero Propulsion Laboratory. By October the Army had decided that the two organizations



Typical machine shop at McCook Field, c. 1920.

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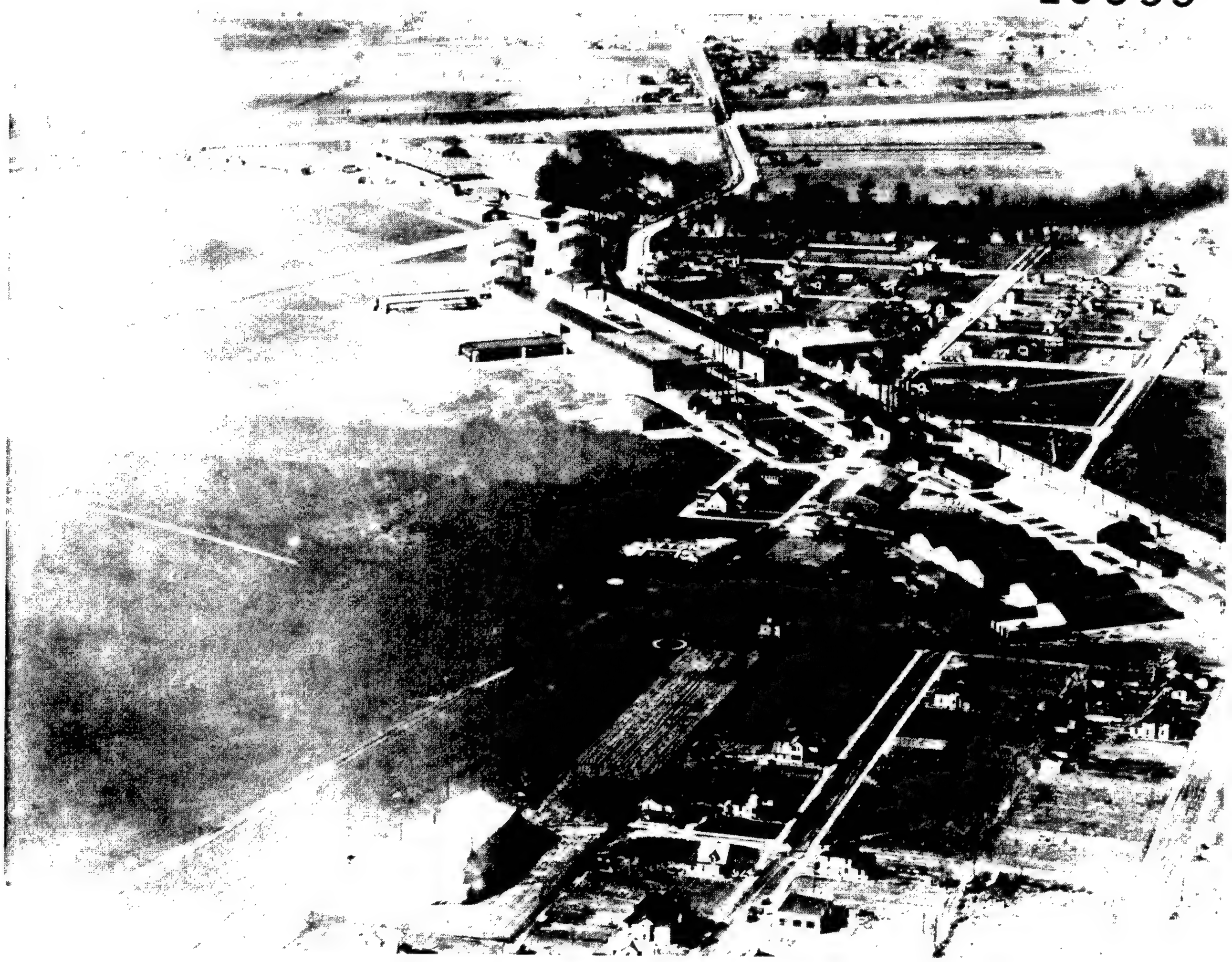
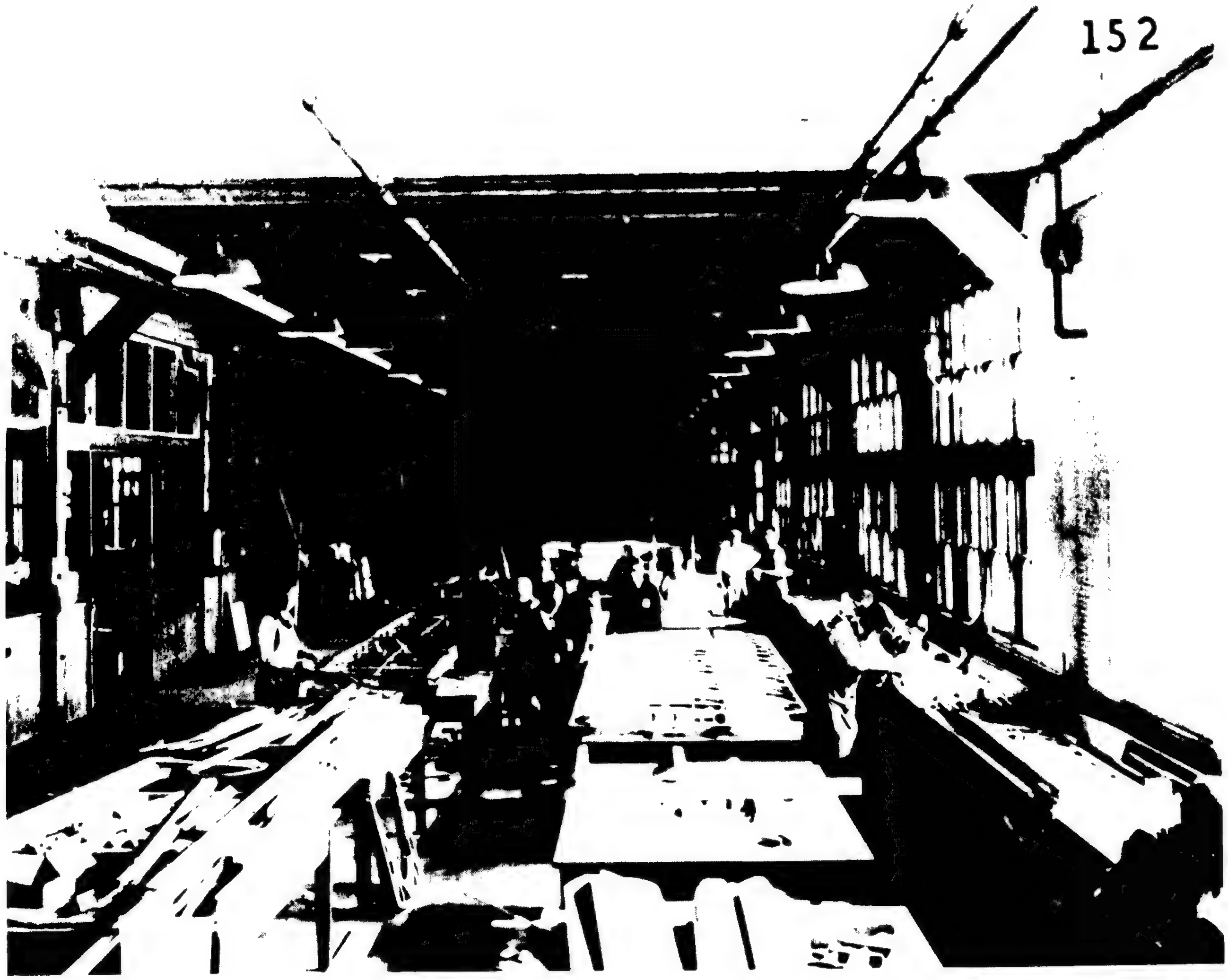


Aerial View of McCook Field (1922), showing the aerodrome.

would function better as one, and they were reunited as the Airplane Engineering Department. The NACA labs at Langley Field were already inadequate, and the Army launched a search for a permanent home for the AED. A group of prominent Dayton industrialists purchased land along the Miami River just north of downtown Dayton and persuaded the Army to establish its second aerodrome there. Thus in November 1917, the Airplane Engineering Department (AED) was established at McCook Field. Langley became headquarters for the Army's research on aerial photography, bombing, and radio communications, and foreign aircraft were also studied there. McCook's mission was to be the development of engines and airframes, as well as weapons and reconnaissance devices. Signal Corps Office Memorandum 11, authorizing engineering research at McCook, may be considered the birth certificate of what became the Flight Dynamics Laboratory.

Familiarly known as the "Airplane Lab," the AED was immediately successful, perhaps because -- as Lois Walker and Shelby Wickam point out in *From Huffman Prairie to the Moon* -- it operated like a private industry. The Lab's close connection with industry made it unique among the world's aeronautical research facilities, and this complex interrelationship has continued to the present day.

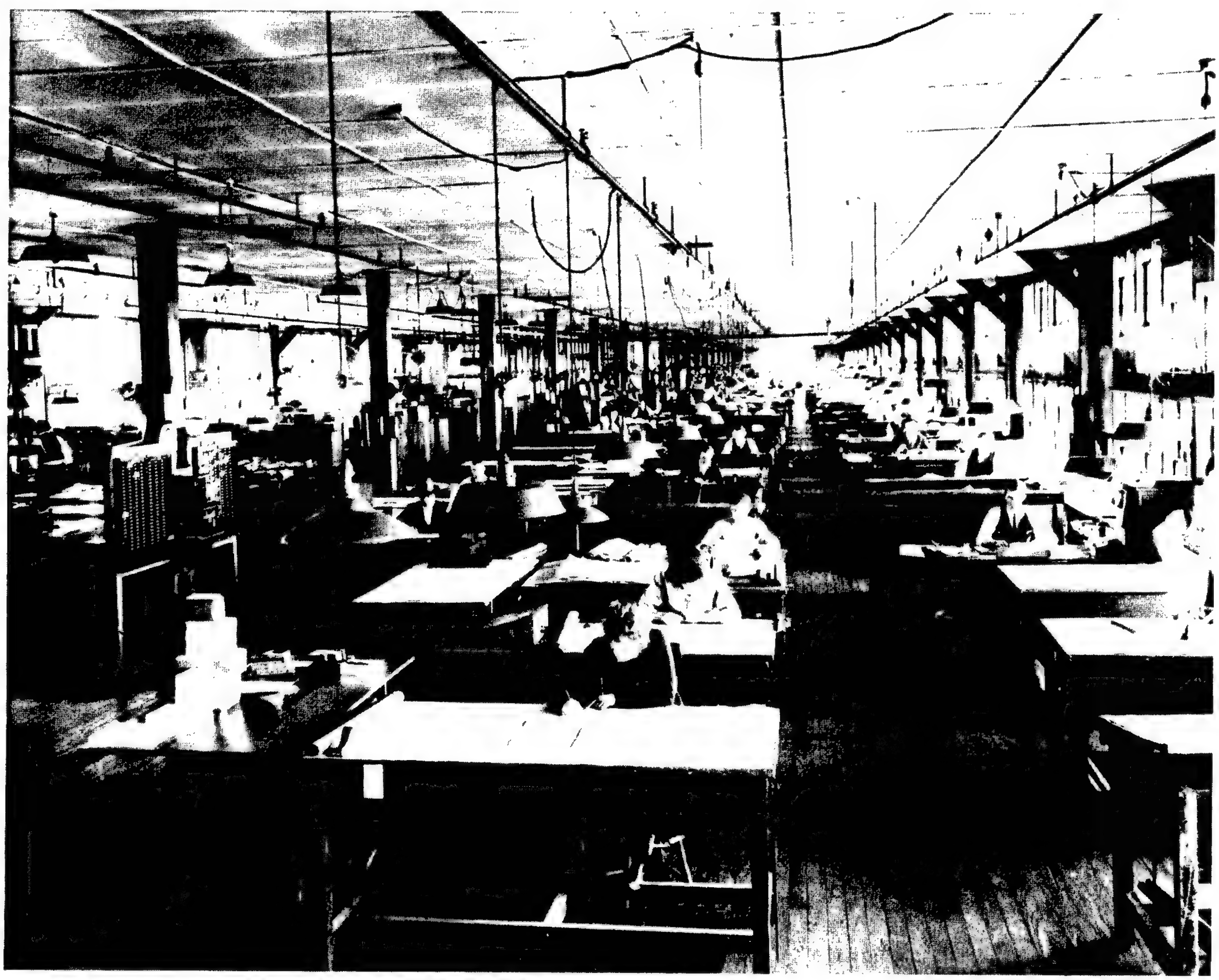


In 1918 the Army sometimes built its own planes. Wing construction at McCook Field.

The American experience in World War I clearly demonstrated that air power would play a key role in future military operations. On 24 May 1918 the Air Service was established in response to America's air power needs: not yet a new branch of the military services, though its commander reported directly to the Secretary of War and no longer to the Signal Corps. During the summer of 1918, as the war in Europe was winding down, the Air Service absorbed several existing units, including the Airplane Engineering Department at McCook Field. The department now had three subdivisions: Production Engineering, Business and Military Headquarters, and Experimental Engineering. The third and largest unit was the ancestor of today's Flight Dynamics Lab. Experimental Engineering "owned" most of the physical facilities at McCook, from the drafting tables to the experimental labs to the fabrication shops, as well as the airstrip along the Great Miami River where experimental craft were flight tested. The first military wind tunnel testing was performed at McCook Field. The shops, according to an

early history, were "equipped for constructing an airplane complete in every detail, from an eighteen cylinder engine to the smallest, most intricate device."

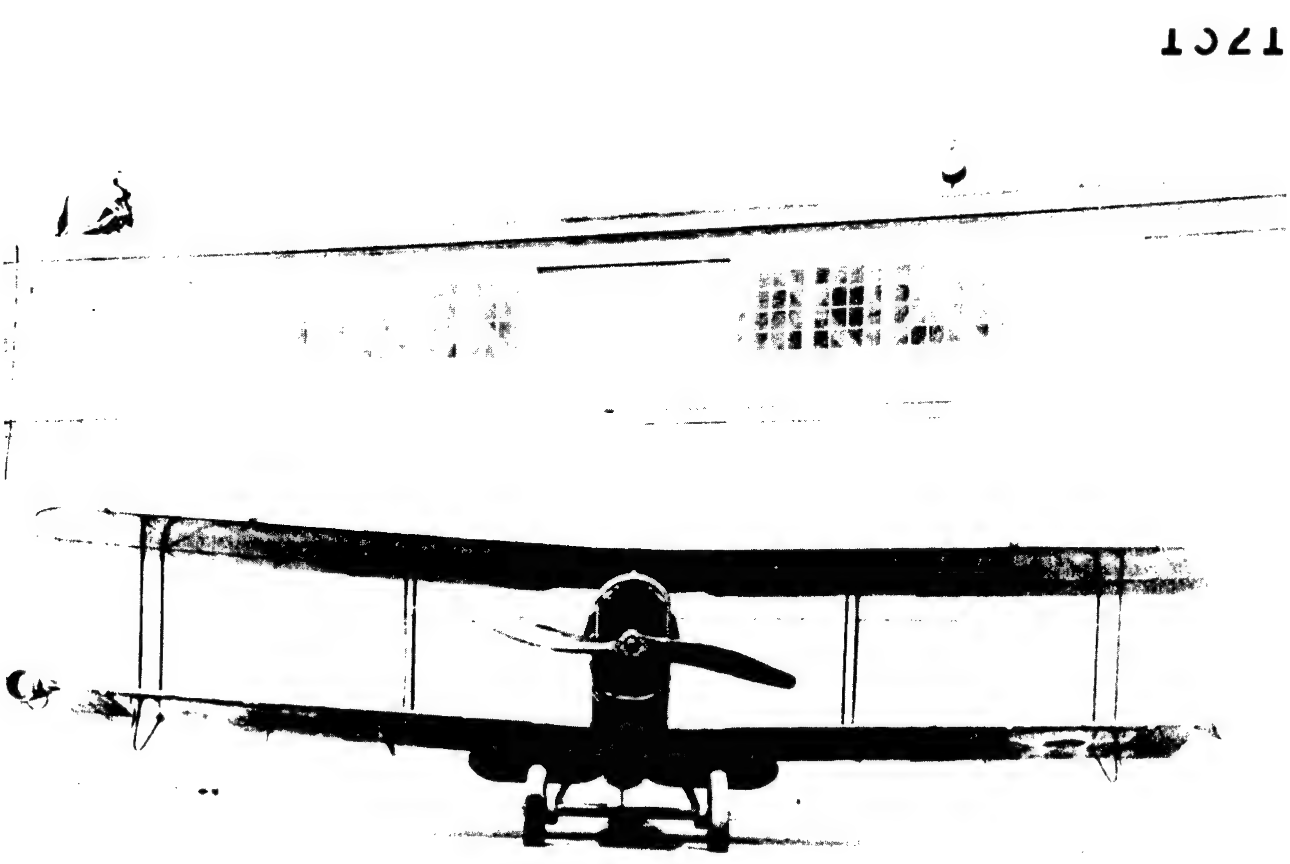
The first accomplishments of the Engineering Division, during and just after the war, involved the adaptation of superior European designs for American use. In addition, the labs developed bomb sights and bomb racks, and mass production and assembly line techniques were improved. After the war the first controllable and reversible pitch propellers were designed at



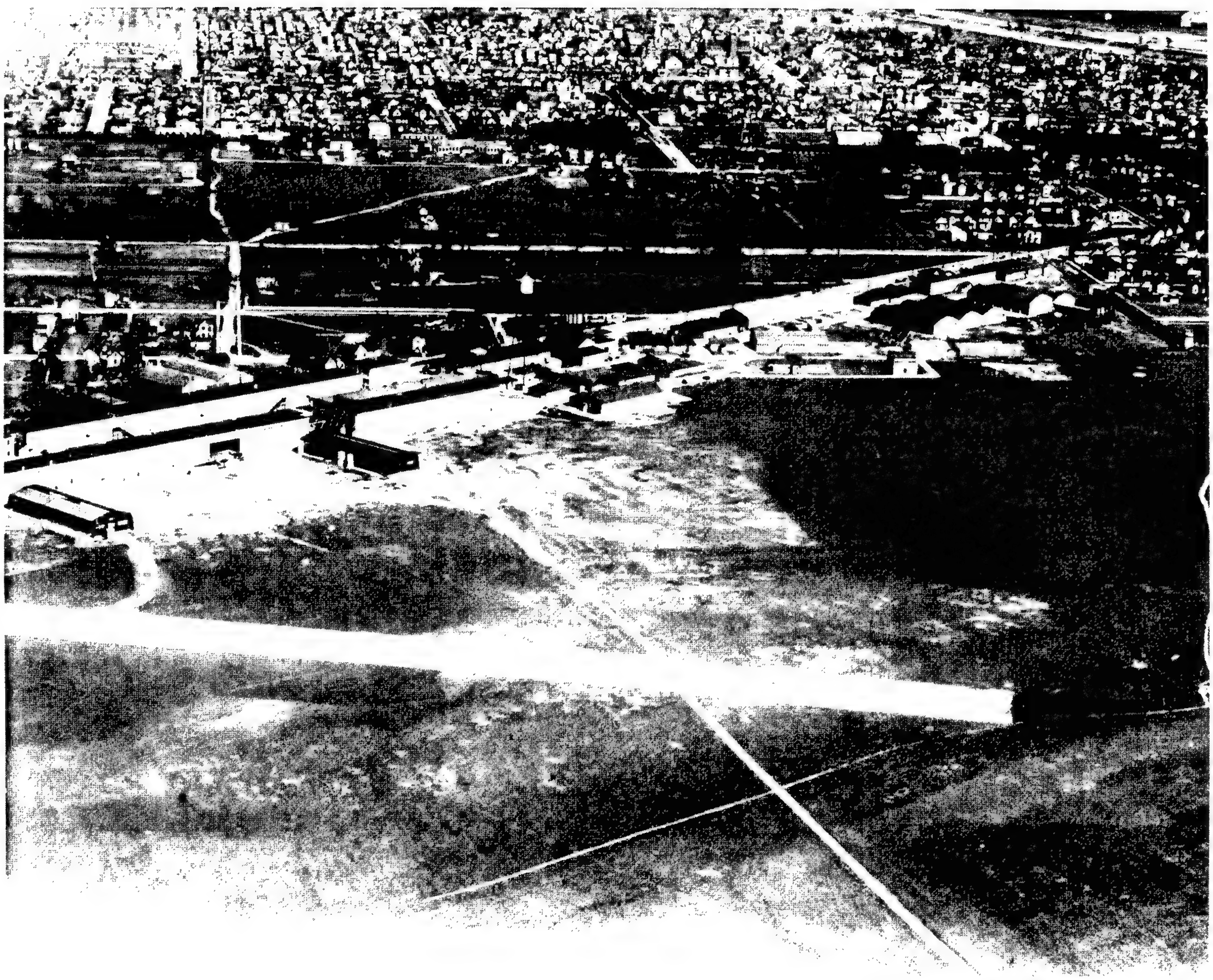
It took an army of engineers and draftsmen to support early airplane design at McCook Field.

McCook, as well as aircraft engine superchargers. Bullet-proof, leakproof fuel tanks were tested; a magnetic clock, an ambulance airplane, mapping and night observation cameras, and a free-fall parachute were developed.

Like any military unit in its infancy, the Air Service went through a series of organizational refinements during 1918. The end of the Great War permitted the allocation of more resources to research and development, and McCook Field benefitted accordingly. In 1919 the Airplane Engineering Division became simply the Engineering Division, and it continued operating under that name until the creation of the Army Air Corps in July 1926. The division's airframe operations were known collectively as the Airplane Section, but most insiders continued to call it simply "the Lab."



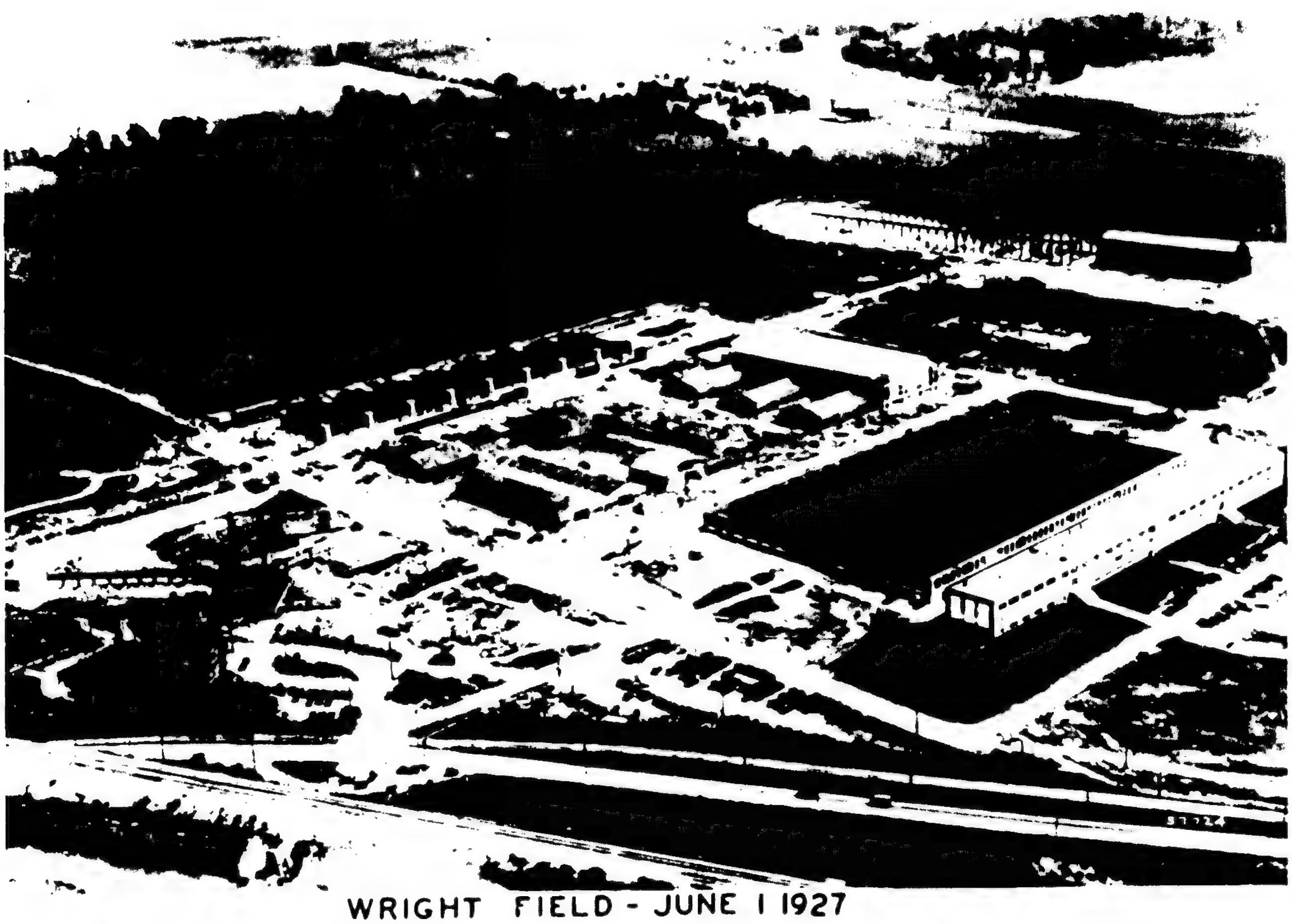
DeHavilland DH-4 used to test landing lights at McCook Field (1922).



Aerial view of McCook Field showing aircraft hangers, landing strip and engineering buildings.

By the mid-twenties the Airplane Lab had far outgrown the facilities at McCook Field, and the Army repeatedly requested an expansion. Unfortunately, for some years after the war Congress was not inclined to appropriate large amounts of money for new military facilities. Again a consortium of Dayton businessmen and industrialists took the initiative, locating and acquiring the land that was to become Wright Field. The establishment of the Army Air Corps underlined the need for improved facilities, and in 1927 the McCook labs were closed and the equipment moved to the present Area B of Wright-Patterson Air Force Base.

The Flight Dynamics Laboratory now stands on the hillside above the old aerodrome, the present site of the Air Force Museum. The new Air Corps Materiel Division took responsibility



Wright Field under construction (1927).

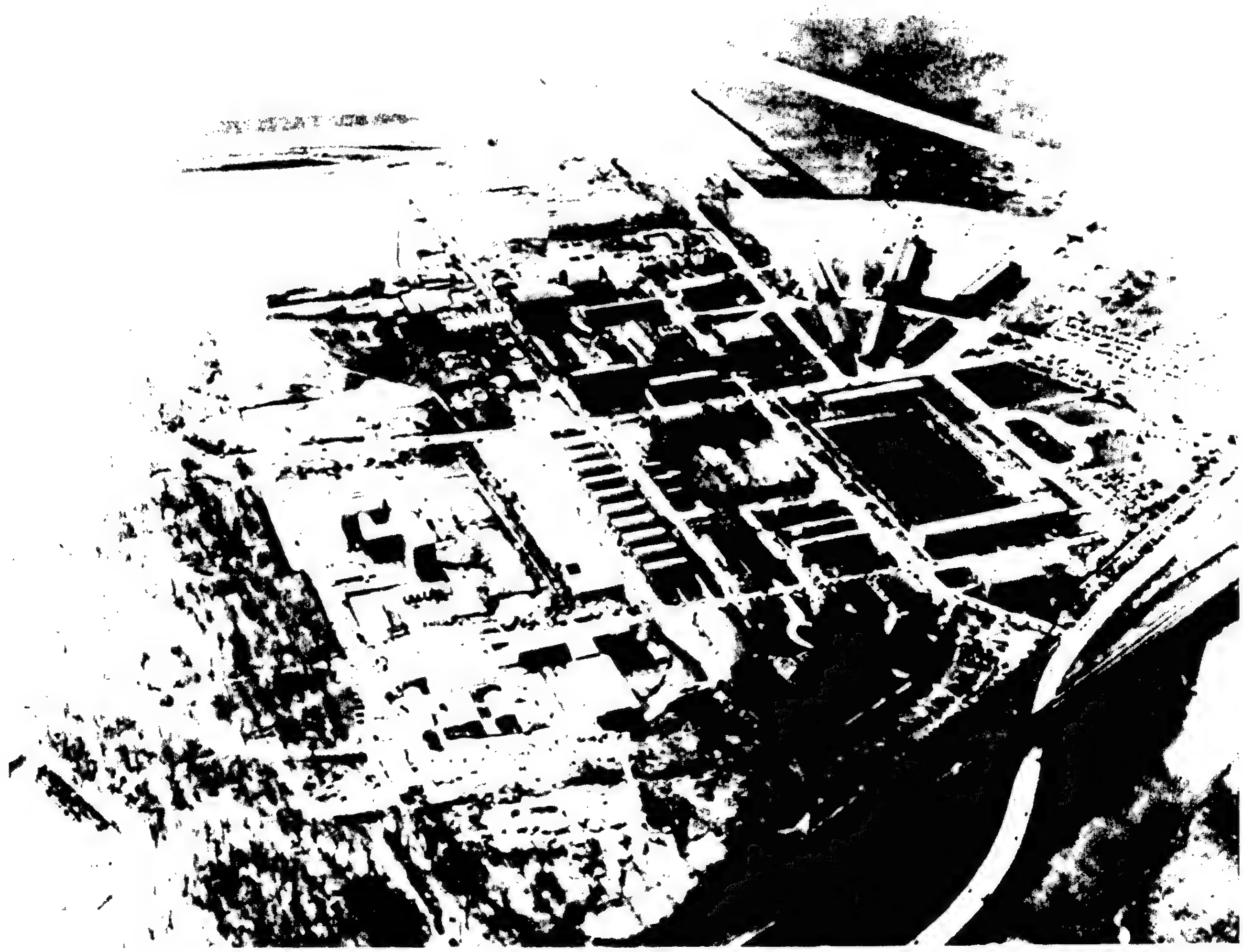
for research and development. One of its six subunits was the Experimental Engineering section, which managed eight laboratories and also had charge of supply, procurement and maintenance. There were two principal branches: Airplane Lab, the ancestor of the FDL; and Power Plant, now the Aero Propulsion Laboratory.

The Airplane Lab grew exponentially during the decade and a half following the move to Wright Field, pioneering such developments as pressurized cabins, helicopters and autogiros. In

April 1939 it was formally designated the Aircraft Laboratory. When World War II broke out Wright Field was America's most advanced facility for aircraft research and development.

The Materiel Division was transferred to the new Army Air Force in 1941 and assumed Command status in 1942; after several organizational changes it 'joined' the USAF in 1947. In 1951 the Lab was detached from the Air Materiel Command and became one of the twelve organizations in the Wright Air Development Center, under the newly established Air Research and Development Command. The succeeding chapters of this book are organized according to the types of research conducted in the WADC: flight control, equipment, aeromechanics, structures and dynamics and advanced development programs.

Three of the Aircraft Laboratory's facilities in the 1940s. Building 50 was Headquarters until the early 1950s.



Southwest view of Wright Field on 20 December 1941. Note the wide variety of aircraft parked near the hangars.

The second World War, like the first, brought about a revolution in American aircraft research and development. General Hap Arnold, advised by Dr. Theodore von Karman, was among the first to recognize German superiority in the R&D field, and the two men were instrumental in putting together the Scientific Advisory Board. Immediately after the end of hostilities in 1945 the SAB visited Germany and acquired an array of German technologies and equipment, in some cases dismantling research facilities and moving them to the United States. The SAB was also responsible for Project Paperclip, which recruited German scientists for the postwar R&D effort. Paperclip brought a number of outstanding researchers to Wright-Patterson, as well as to laboratories elsewhere. Their presence profoundly affected research and development in the 1950s and beyond. General Arnold had also studied the relationship between German industry and military R&D, and recommended changes that have greatly increased the productivity of the military/industrial partnership in this country. Though the Airplane Lab and its

predecessors had always contracted with industry to build the technologies created at McCook and Wright Fields, after the war there was a new emphasis on shifting R&D itself to the contractors. The role and function of Air Force laboratories thus became radically different. Beginning in the early fifties the FDL and its predecessors began to provide funding for external R&D work, and as new systems went on line the companies' profits were plowed back into further research. Thus the laboratories were no longer the prime movers of new R&D, but instead assumed a 'management' function. They established technological standards and became data repositories for the technological lessons learned in the new process. They studied technological trends and predicted future directions, permitting government funds to be channeled into projects that would serve the future needs of the Air Force. Of course, many other factors have impacted on this symbiotic relationship between the labs and industry. Certain individuals had a powerful influence on the direction taken by new research, as did changes in funding from one administration to the next. As noted elsewhere, the war in Southeast Asia affected FDL's focus in numerous ways.

Since the late forties the Air Force's Scientific Advisory Board (SAB) has been instrumental in determining the directions taken by research and development at the Flight Dynamics Lab. Five major science and technology forecasts have been undertaken since the end of World War II, and all have impacted the Lab in fundamental ways. *Toward New Horizons* (1945) was a summary of the technologies developed in response to the demands of the war, with proposals as to what directions aeronautical R&D should take in peacetime. Under the direction of Theodore von Karman, this report set the pace for all subsequent Air Force R&D planning. The *Woods Hole Summer Studies*, produced in 1957 and 1958 by gatherings of scientists at the Woods Hole Institute in Massachusetts, established guidelines for the military development of aerospace technology. It did not, however, address the serious question of regaining America's lead in basic research after the unpleasant surprise of the Sputnik launching. *Project Forecast* (1964), coming as it did just after the establishment of the present Flight Dynamics Laboratory, was critical in determining the nature and organization of R&D at the Lab. It was directed by General Bernard Schriever, commander of ARDC and then of the Air Force Systems Command. This project considered not only the state and future possibilities of technology, but also proposed that R&D decisions must be linked to national policy. Its twenty-five volumes included proposals for weapons to fight small-scale nuclear wars as well as conventional conflicts; it called for development of low-yield nuclear weapons, new transport aircraft, creation of new light composites, and research in vertical take-off and landing (VTOL) concepts. It was due largely to the *Project Forecast* report that FDL concentrated heavily on aerospace research during the mid-sixties, and then turned back to more conventional work in response to the Vietnam conflict. *New Horizons II* (1975) had an impact on the reorganization of the Lab in the mid-seventies, concentrating on making research and development more cost-effective and efficient. It proposed further development in the areas of data processing, survivability and maintainability, laser weapons, and all-weather flying, among others. Currently the Lab is working to implement some of the findings of *Project Forecast II* (1986), which called for a new emphasis on basic research and further aerospace work, with less attention given to national policy concerns. Advanced computer research, ultrastructured materials, anti-proton technology, the National Aerospace Plane, and satellite array radar were among its proposals. Many of the current projects described in the following chapters owe their origins to *Forecast II*.

Scarcely less significant than the impact of the SAB has been the introduction of analog and then

digital computers. The 'computer revolution' meant radical changes in every aspect of military research and development, and FDL has always led the field in adapting and creating new computer techniques for design and testing. Computers are now essential to an understanding of fluid dynamics, structural analysis and many other aspects of aircraft design. On-board computers, as distinct from those used for gathering and processing design data, have become an integral part of flight control and other systems, and have made possible entirely new technologies such as control-configured vehicles (CCVs). As digital computer technology has advanced and costs have dropped, the application of computers has become ubiquitous in aircraft development: brake control, sensor data processing, instrument operation, environmental control, fire control systems, electronic warfare -- all now depend on computers.

In 1953, just before its reorganization, the Aircraft Laboratory consisted of:

(1) the Aerodynamics Branch, at that time working on performance characteristics of advanced aircraft, range extension, and flight problems of coupled aircraft;

(2) the Dynamics Branch, responsible for flutter and vibration analysis and prediction and acoustics problems;

(3) the Design Branch, conducting aircraft design data gathering and analysis programs;

(4) the Special Projects Branch, responsible for certain types of equipment such as crew escape systems, bearings and cables;

(5) the Mechanical Branch, investigating landing gear, tires, brakes and hydraulic and pneumatic control systems;

(6) the Structures Branch, which performed static and dynamic testing and established criteria to improve structural designs; and

(7) the Wind Tunnel Branch, responsible for aerodynamic wind tunnel testing.

The launching of the Soviet satellite "Sputnik" in 1957 fomented a revolution in American technical and scientific planning. During the late fifties Washington was searching for ways to improve the structure of military research and development, and it was clear that a more efficient organization of the Wright Field labs was necessary. In December 1959, as a first step, the WADC became the Wright Air Development Division, and in April 1961 the new Air Force Systems Command took over the major aspects of R&D at Wright-Patterson and elsewhere. Most of the research facilities in Area B now became part of the Aeronautical Systems Division, which thus replaced and expanded the old Experimental Engineering Division. Research, technology, procurement and production were all included under the ASD umbrella. The new Aeromechanics Division included Flight Control, Flight Dynamics (the Aircraft Lab), Flight Accessories, and the Propulsion Lab. (Note the distinction between the old Air Force Flight Dynamics Lab and the current FDL, which is assigned to the Air Force Wright Aeronautical Laboratories (AFWAL) rather than directly to the Air Force Systems Command.) This period of realignment, during which FDL was directed by Col. John P. Taylor, was part of the Kennedy administration's efforts to consolidate, streamline and upgrade the nation's military research efforts. In April 1962 the new Research and Technology Division was formed and headquartered at Andrews Air Force Base near Washington. RTD answered directly to the Air Force's Assistant Secretary for Research and Development, then Brockway McMillan. Since that time the Assistant Secretary has been primarily responsible for determining the Lab's overall direction in R&D.

Though these changes were initiated in reaction to Sputnik, the creation of the present FDL was largely the product of the Kennedy administration. President Kennedy and his Secretary of Defense, Robert McNamara, were committed to staying ahead of the Soviets in the space race and putting a man on the moon before the end of the decade. FDL as well as NASA and other agencies received new funding, and in the

early sixties the primary technological emphasis was on aerospace vehicles. The Vietnam War, later in the decade, required the Lab to concentrate more heavily on conventional aircraft and weapons systems, while NASA continued space research; but FDL continued to contribute to the American space program throughout this period, often without much credit.

The Aeronautical Systems Division was by far the largest single component of the AFSC, and played the leading role in the massive reorganization of Air Force labs and test facilities in the early sixties. In July 1962 the AFSC upgraded RTD to a field organization with headquarters at Bolling Air Force Base in Washington, though Wright-Patterson continued to be the real heart of the operation. Major-General R. G. Ruegg, commander of ASD, appointed Brigadier General Fred J. Ascani to organize and implement the Laboratory's new responsibilities. Ascani was then serving as deputy commander of the B-70 program, at that time one of ASD's major projects. Ascani set up a task force consisting of eight senior officers and civilians, in August 1962. General Ruegg understood that his task force would profoundly reshape the nature and direction of aeronautical research for many years to come. As he told his colleagues, they had "five months to come up with an organization and six months to make it work."

The task force had been presented with a unique opportunity to improve the Air Force's R&D capabilities. At the same time, they did not wish to disrupt existing organizational structures any more than necessary. It was a delicate task: at stake was the future of what was arguably the most advanced and productive aeronautical research facility in the free world. In October the

Maj. Gen R. G. Ruegg

Brig. Gen. Frederick J. Ascani

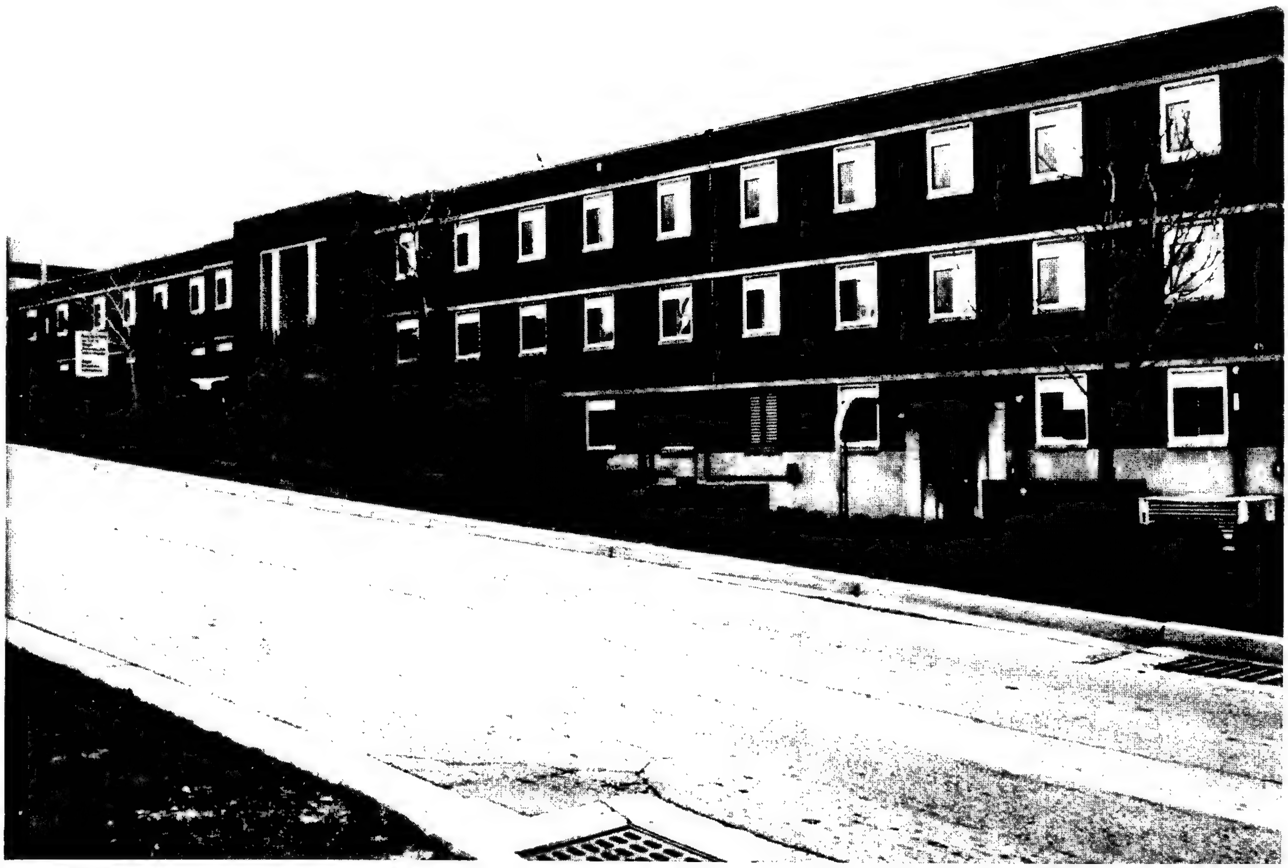
task force met with Major General M. C. Demler, commander of RTD, to finalize its report. In November its plan was presented to the Systems Command Headquarters and later to the AFSC commander, General B. A. Schriever. Amended recommendations were forwarded to RTD headquarters and to Assistant Secretary McMillan, who approved the plan in March 1963. An operations order soon followed, and one of the largest reorganizations in Air Force history was under way. General Demler assumed overall command. General Ascani, as acting vice-commander, supervised the transitional phase at Wright-Patterson during the spring and summer of 1963. Realignment was completed, with minimal disruption to base operations, by October 25.

Thirteen separate laboratories at Wright Field were consolidated into four new labs: Flight Dynamics, Propulsion, Avionics, and Materials. The former Flight Control, Flight Dynamics, and Flight Accessories labs became the nucleus of the new Flight Dynamics Lab; the test facilities were previously under the Directorate of Engineering Test. The original divisions of the new FDL were Flight Control, Vehicle Dynamics, Vehicle Equipment, Flight Mechanics, and Structures. In addition there was a Systems Support Office, responsible for technical support to other DOD organizations and liaison with other laboratories; a Plans and Program Office, which conducted the fiscal and documentary functions of the Lab, as well as short- and long-range project planning; and the Executive Office, which provided personnel and administrative services. The Director, who was usually an Air Force colonel, fashioned strategies for solving problems within the Lab and was FDL's advocate to other agencies. The deputy director had more direct responsibility for the day-to-day management of the Lab. The purely scientific aspects of the Lab's work were under the supervision of the Chief Scientist. At that time the bulk of FDL's research was in the aerospace field, and the Lab was often far ahead of NASA in the development of space technology. But the war in Southeast

The new Building 45 became FDL headquarters in the early sixties.

Asia, along with other considerations, prompted greater emphasis on conventional aircraft. In the last two decades the emphasis has been on strategic deterrence -- although the Lab does create tactical weapons, it is always essential to keep the "big picture" in mind so that the United States will be prepared to answer any type of enemy threat.

In terms of technique, the primary change during the seventies and eighties has been in the realm of technology integration. As new aircraft and weapons systems became more complex, Lab scientists recognized that it made no sense to develop and test new technologies in isolation from other systems. Col. Charles Scolatti, Lab commander from 1971 to 1974, guided the Lab into the systems approach that it still follows today. In developing new technologies the divisions of the Lab now work more closely with each other and with outside organizations, and



Building 45 has been headquarters of the Flight Dynamics Lab for more than a quarter of a century.

the approach has paid off in many ways. The 1988 reorganization, which created the Wright Research and Development Center, is expected to improve the Lab's efficiency in all areas.

Today as we approach the 1990s the pendulum is swinging back toward space research. The National Aerospace Plane program and other aerospace projects such as the Strategic Defense Initiative now have high priority. But FDL engineers have always been on the cutting edge of aeronautic and space technology. The Lab produced the first lifting body to fly at re-entry speeds, as well as America's first vertical take-off and landing aircraft with direct jet lift and diverted thrust lift cruise engines. During the past two decades all-weather landing technology has been advanced, and an air cushion landing concept was explored. FDL pioneered in cryogenic research, and was primarily responsible for several experimental aircraft like the X-24 and the X-29. Today's technology integration concept, first applied to the AFTI/F-16, has also been applied to the AFTI /F-111 and the X-29 as well as the Integrated

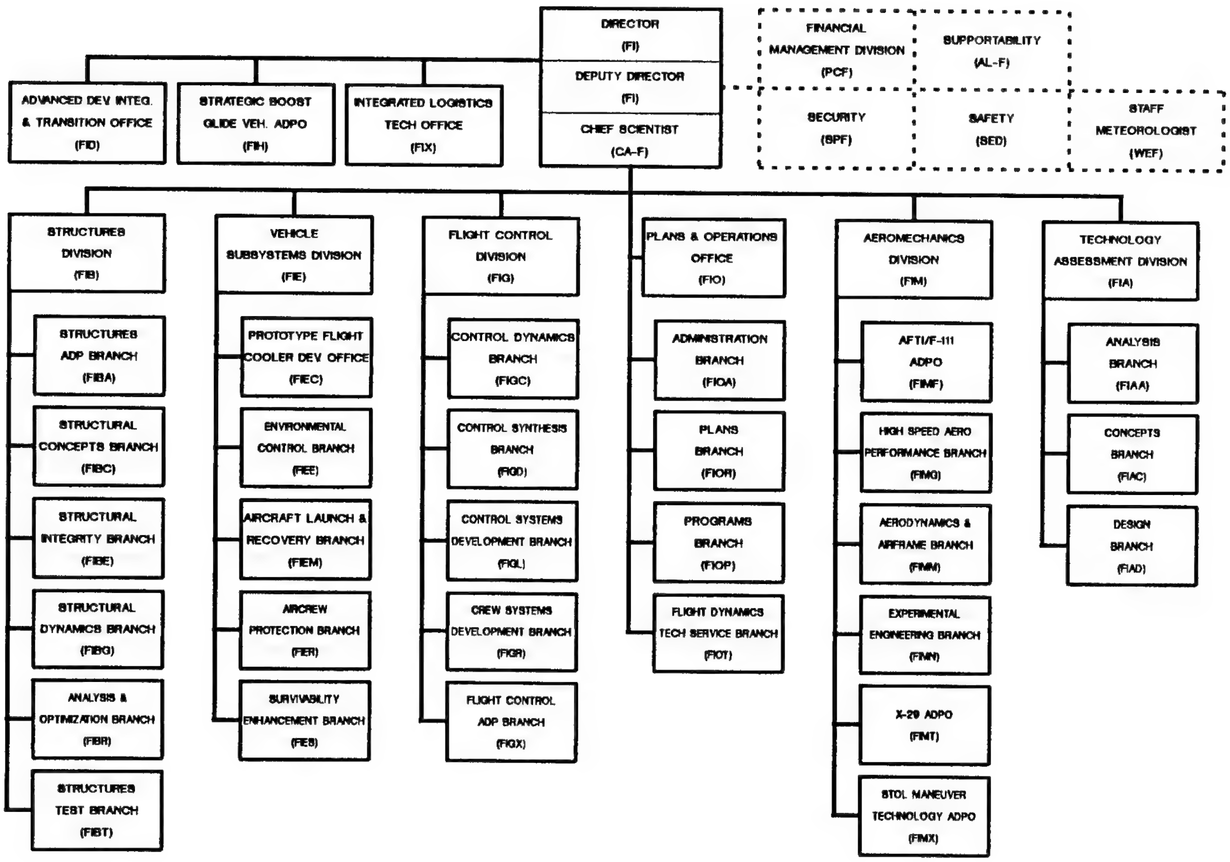
Flight/Fire Control concept. The STOL and Maneuver Technology Program, which is now testing with an F-15 aircraft, has contributed to a better understanding of the take-off and landing aspects of the flight regime. Crew escape systems and aircraft survivability, among other fields of research, have saved countless lives over the years. The hypersonic glide vehicle, a matter of interest at Wright Field since the 1950s, was first explored in the X-24 program, and came into its own with the development of the space shuttle. This technology continues to advance as FDL contributes to the National Aerospace Plane project. The Large Space Structures Program will benefit SDI and space station technologies. Nearly every airborne American weapons system -- aircraft and missile -- is at least in part a product of FDL. During the past quarter century, basic and theoretical research have not been neglected. The Lab has turned out a large number of computer programs that are now indispensable to aircraft designers the world over.

Flight Dynamics Laboratory in 1988

The quarter century since the creation of the present Flight Dynamics Laboratory has seen a number of reorganizations, though the basic mission has remained unchanged. At present there are five divisions responsible to the Director: Vehicle Subsystems (formerly Vehicle Equipment); Flight Control; Aeromechanics (including aerodynamics and related disciplines); Technology Assessment; and Structures (formerly Structural Mechanics, and before that, two separate divisions: Structures and Dynamics). The Plans and Operations office reports directly to the head office. Other units include the Advanced Development Integration and Transition Office, and the Hypersonic Technology Office. The Financial Management Division, Supportability, Security, Safety, and the Staff Meteorologist office all report to the director's office. The AFWAL Integrated Logistics Technology Office (ILTO) is also located within FDL. It is responsible for the development of logistics analysis tools that enable program offices to accomplish the trade-off studies needed to set reasonable goals. Together with AFWAL's Logistics Office, ILTO coordinates program advocacy and technology transition.

Many of the present and former employees interviewed for this study emphasized that the programs and technologies of the Flight Dynamics Lab are an interconnected whole. New technologies are explored, branch off into other areas, and sometimes end up producing aircraft and equipment that would have been impossible without input from many different groups, branches and divisions. Some investigations turn out to be dead ends, but nothing is forgotten: often an idea that was considered and set aside is revived, a decade or two later, as a component in some then undreamed-of technology. Several interviewees also stressed the importance of basic research, since radically new technologies sometimes come out of work that has little apparent connection to military needs. In the last analysis, the Lab decides whether to pursue a project based on three factors: the Air Force's need for the proposed technology; its technical merit and feasibility; and the cost/benefit ratio. This volume attempts to trace the history of a representative sample of such technologies, both basic and applied, as they evolved through the years and through frequent shifts and reorganizations of the Lab.

As it moves into the 1990s, the Flight Dynamics Lab expects to emphasize four major development areas: hypersonic vehicle technology, short take-off and landing (STOL and STOVL) vehicle, fighter battle management, and reliability/maintainability and supportability for existing and future aircraft. These future directions have been partly defined by the FORECAST II Project, which has identified Strategic Defense Initiative and Hypersonic Vehicle research as top priorities. The Lab will continue to work alongside other organizations such as NASA on certain projects, many of which are described in this book.



Air Force Flight Dynamics Laboratory Organizational Chart (1988).

Technical Services

By 1973 existing technical support arrangements were no longer sufficient for the needs of a growing Flight Dynamics Laboratory. Accordingly, the Technical Services Division was created to formulate, plan, manage and direct technical support in the following areas: Computer Services, Independent Research and Development, Technical Information, Visual Aids, Material Control, Military Construction and Modification, Environmental Assessment, Precision Measuring Equipment, Shop Support, Petty Cash, and Technical Support Logistics. The importance of managing and planning the Lab's budget cannot be overemphasized: research and development is expensive, and it is often difficult to predict where a project will end up and how much it will cost, but no progress could be made otherwise. Former Deputy Director William Lamar likens the process to tearing down an entire mountain to find the single diamond buried inside.

The Computer Services Branch started out with a CDC 1700 Batch Remote to the CDC Cyber 74 located in the Aeronautical Systems Division's computer center. It maintained the Laboratory Automated Data Processing Inventory and provided information systems services to the entire Lab. The IRAD Branch supported independent contractor research, and the Technical Support Branch provided logistics support, including fire and safety needs, procurement of unique and hard-to-find equipment, and maintenance of test facilities. The Laboratory Material Control Activity Branch was responsible for acquisition, and storage of materials and supplies. The Technical

Information Branch administered the Scientific and Technical Information Program (STINFO), a library of technical data; the Visual Aids Branch assisted other divisions in the design of presentations, and conducted tours and briefings. Today the Plans and Operations Office has taken over many of these functions, including the planning for this book.

FLIGHT CONTROL DIVISION
FIG

CONTROL DYNAMICS BRANCH
(FIGC)

DESIGN PREDICTIONS
FLYING QUALITIES
CONTROL ANALYSIS

CONTROL SYNTHESIS BRANCH
(FIGD)

ENGINEERING SIMULATION
SYSTEMS OPERATIONS

CONTROL SYSTEMS DEVELOPMENT BRANCH
(FIGL)

CONTROL DATA
CONTROL TECHNIQUES
CONTROL MANAGEMENT

CREW SYSTEMS DEVELOPMENT BRANCH
(FIGR)

DESIGN AND EVALUATION
INFORMATION INTERFACE
FIGHTER TECHNOLOGY

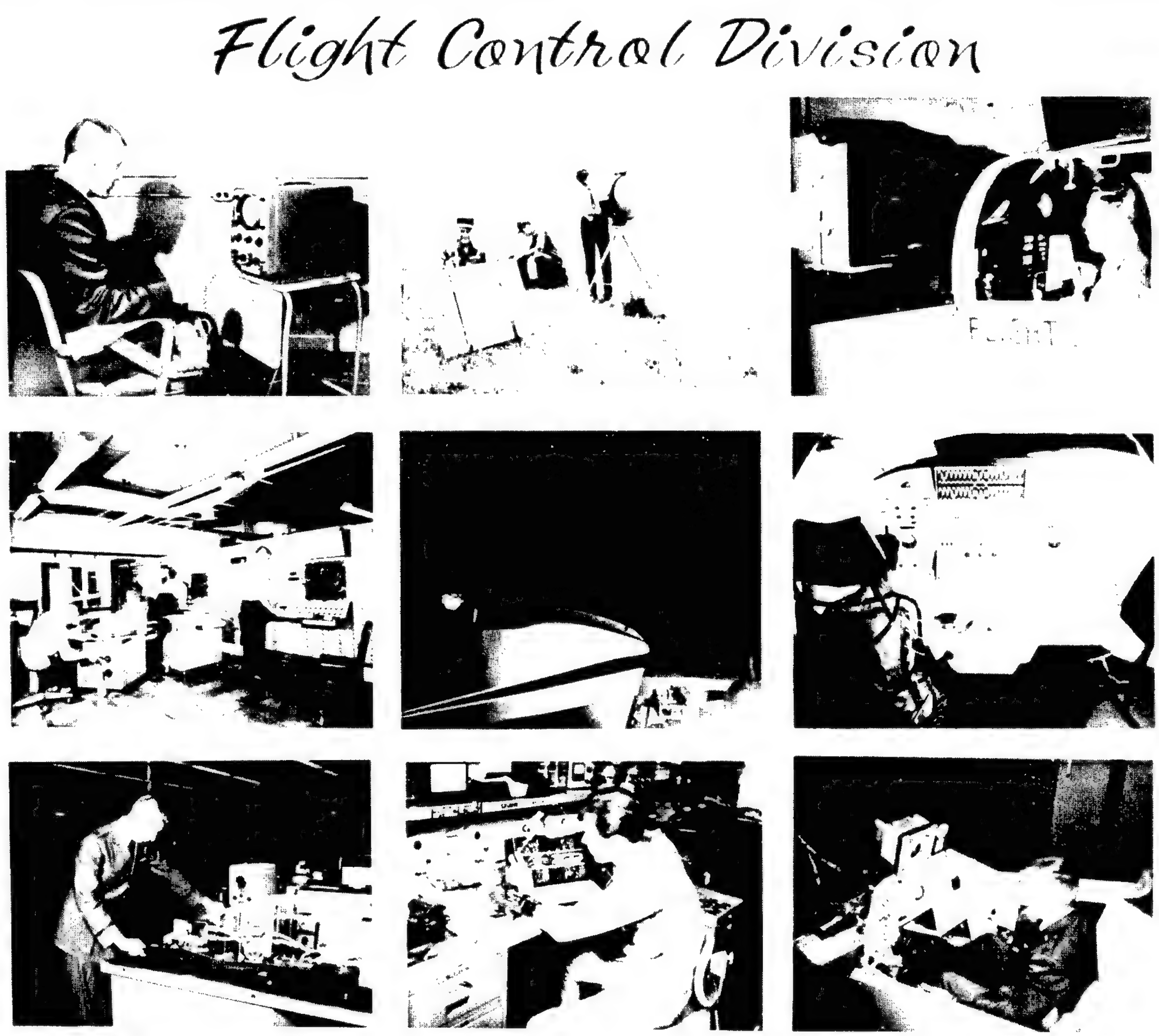
FLIGHT CONTROL ADP BRANCH
(FIGX)

ADVANCED CONCEPTS FLIGHT RESEARCH
CONTROL APPLICATIONS
ADVANCED FIGHTER TECHNOLOGY
IN-FLIGHT SIMULATOR

Flight Control

"The inability to balance and steer still confronts the student of the flying problem. . . when this feature has been worked out, the age of flying machines will have arrived, for all other difficulties are of minor importance." -- Wilbur Wright, 1901

The systems and technologies concerned with controlling the flight path and related functions of an aircraft are collectively known as "flight control." Any vehicle, airborne or otherwise, has value and utility only insofar as its direction and velocity can be controlled. The earliest pioneers of aviation recognized this fact, and flight control was a prime concern of the Flight Dynamics Lab and its predecessors from the beginning. Control components and technologies were originally the responsibility of the old Mechanical branch of the Aircraft Lab, and later of the Control Equipment branch. The McCook Field Airplane Lab initiated basic research in navigational



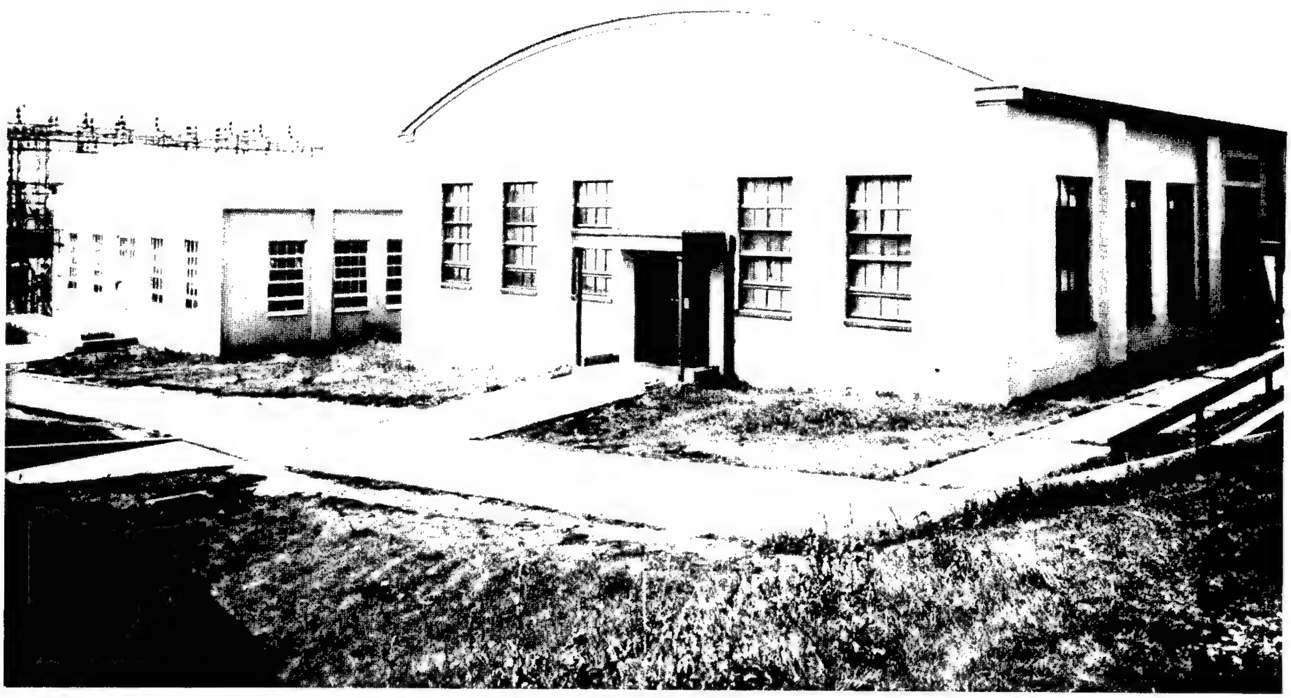
The Flight Control Division conducts research in a wide variety of areas, as this composite from the mid 1960s shows.

instruments, and created such new devices as the "drift indicator." Older instruments such as the ammeter and tachometer were adapted for aircraft. Some of the theoretical advances made at the turn of the century (e.g., dynamic stability analysis) were first applied extensively at McCook Field, and feedback control theory came under scrutiny in the 1930s at Wright Field. But not until the current "laboratory concept" emerged in the 1950s was flight control recognized as a discrete system discipline requiring its own research facilities. Changes in aircraft performance and control technology after World War II mandated a more integrated research approach. As pioneer George Yingling puts it, "instruments, autopilots, navigation devices, etc. were all accessories to going safely from here to there, but not primary to aircraft design." Because so many different aircraft systems had to be "controlled," research in this area had always been fragmented among various labs. For example, in the old Engineering Division, the Equipment Laboratory was responsible for cockpit instrumentation, while the Armament Laboratory developed autopilots. The All Weather Division, responsible for what was later termed technology integration, had a well-earned reputation for big budgets and showy demonstrations of innovative technology, but had little communication with labs doing more prosaic work in component improvement. In short, there was no "systems approach" to problems of flight control.

Among the first to recognize this deficiency was Siegfried Knemeyer of the Communications and Navigation Lab. Knemeyer, a brilliant theoretical scientist and former chief of Technical Development for the Luftwaffe, was recruited under Project Paperclip shortly after World War II. A frustrating experience with assigning responsibility for autopilot development, along with the emergence of a new class of control problems in the transonic regime, persuaded Knemeyer that a unified flight control laboratory was needed. Together with Ray Bryan of the Division headquarters and Chief Scientist Ezra Kotcher from the Wright Air Development Division, Knemeyer took his case to the Air Force. Dr. Kotcher in particular hoped to create a laboratory capable of actually designing and flying new aircraft, not simply conducting research and advising contractors. General Al Boyd, then commander of AFFTC and the Air Force's chief test pilot, enthusiastically supported this effort -- test pilots had long been frustrated by the fact that there was no central "clearing house" to which they could bring flight control discrepancies.

The establishment of a flight control lab, drawing components from other laboratories, would of course mean a wholesale reorganization of all the Wright Field laboratories under the Air Research and Development Command. As George Yingling puts it, a chain reaction was set off which resulted in more efficient organization of R&D functions throughout the Air Force. Ray Bryan, Charles Westbrook and other veterans of that period have vivid memories of the confusion and intense personal feelings engendered as a result of the decision to reorganize. In the case of the new Flight Control Lab, the groundwork was laid largely by George Yingling and Melvin Shorr. During the transition, flight control activities were managed by Col. Aldro Lingard and then by Ray Bryan. The first lab chief was Col. John L. Martin Jr., a command pilot with a doctorate from MIT. Those who remember Martin's tenure praise his ability to inspire a high *esprit de corps*, market the organization and foster creativity.

The Flight Control Laboratory initially (1955) included the Automatic Flight Control section from the Armament Lab,the Instrument and Display Group from the Equipment Lab, the All-Weather Branch, Stability and Control from the Aircraft Lab Aero Branch, and Manual Flight Control from the Aircraft Lab Mechanical Branch. These were reorganized as the Stability and Control Branch, the Control Equipment Branch, the Instrument Branch, and the Control Synthesis Branch. Flying qualities research was then considered an aeromechanics concern.



Buildings 192 and 193 housed some facilities of the Flight Control Lab in the 1950s.

Areas of research included vehicle control dynamics, control science and technology, cockpit instruments, and control component technology. Human and pilot factors, which then came under the heading of experimental psychology, were not included, though several of the Lab's founders campaigned for such a branch. (Siegfried Knemeyer, by contrast, once said that a PhD in experimental psychology was only marginally more valuable than a degree in home economics.) Ray Bryan was able to persuade the Aeromedical Lab to assign two psychologists to Flight Control.

The original flight control facilities were inadequate in the beginning. When organized the Lab was located in buildings 192, 193, 194, and 195, some of which were partially assigned to other units, and there were jurisdictional problems with other labs. In the late fifties the Lab acquired Building 434, a flexible gunnery simulation facility that was no longer in use. This structure had the necessary power supply, air conditioning, and computer rooms for the simulators. Other facilities were added on an as-required basis, but the Lab still lacked a coherent and unifying location. In the 1960s a

Aerial view of today's Flight Control Division Facilities.

temporary steel structure was constructed adjacent to Building 195 to house the simulator terrain board for the flight control simulator. Herbert Basham began lobbying the Air Force Systems Command for a consolidated facility, and plans were under way when Flight Control was incorporated into the Flight Dynamics Lab was organized in 1963. Congress approved an appropriation for Buildings 145 and 146, which were completed in 1974 and 1983, respectively. When the present Flight Dynamics Lab was organized in 1963, the branches of the Flight Control Division were: Stability and Control, Control Display, Control Equipment, and Systems Integration.

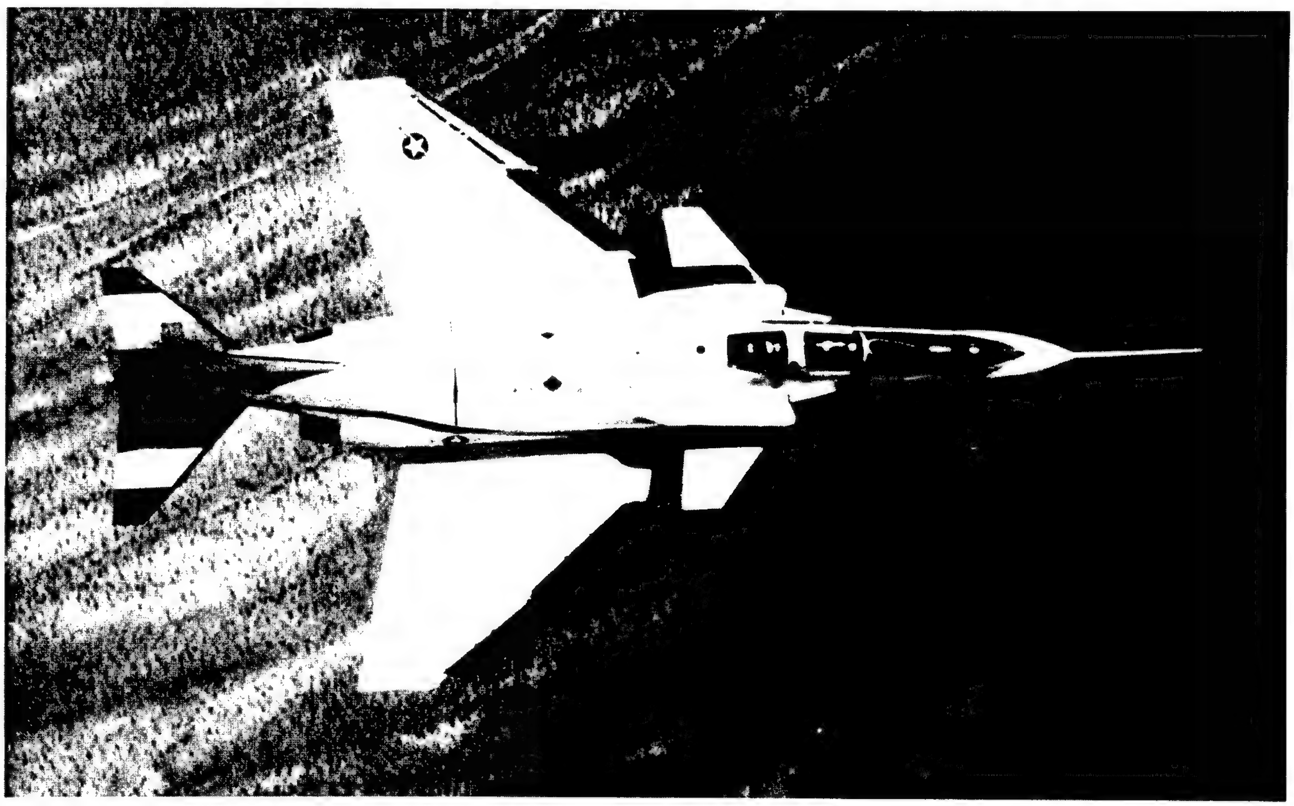
A summary of the Flight Control Lab's accomplishments before the 1963 reorganization would include a wide variety of simulation models, the Datcom (Data Compendium) computer program for estimating stability derivatives, advanced electro-hydraulic servo valves, the "Tee" arrangement of primary flight instruments, the first fly-by-wire throttle control, the Failure Modes and Effects Analysis project, the Control Augmentation System (CAS), and the original air data computers. Many of these innovations are described in this chapter, arranged according to technologies: stability and control, trajectory analysis, flying qualities, control equipment, control instrumentation,

flight instrumentation, control displays, control analysis and optimization, and advanced development programs.

It should be noted that the Flight Control Division, more than other organizations within the Lab, has a close working relationship with the Avionics Laboratory at Wright-Patterson. The Avionics Lab develops new radar and radio technologies, electronic guidance systems, air data sensors, and techniques for electronic warfare. Obviously these technologies are closely related to modern electronic flight control systems, with which they must be closely integrated.

Fly-By-Wire: A Major Flight Control Triumph

During the past half century the Aircraft Lab and Flight Dynamics Lab have been a microcosm of flight control progress. Until the early 1950s all pilot control was exercised through mechanical devices such as rods and cables. This technology does give the pilot a sense of immediate control, but its effectiveness is limited by his/her muscle power. During the fifties the Flight Control Lab (later Division) pioneered in the stability augmentation concept. It was discovered that aircraft stability changes rapidly and aerodynamic loads shift in the transonic and supersonic regimes, creating difficulties beyond the pilot's control. The invention of yaw, pitch and roll dampers with feedback from gyros improved stability, using some electrical connections within the mechanical system. However, if the system failed or reached its limits, key functions could not be corrected manually; this meant that the system had authority limited to control deflections that the pilot could override. Full authority (as well as control over flutter and other parameters) could be achieved only by moving to an all-electrical flight control system with redundancy backup.

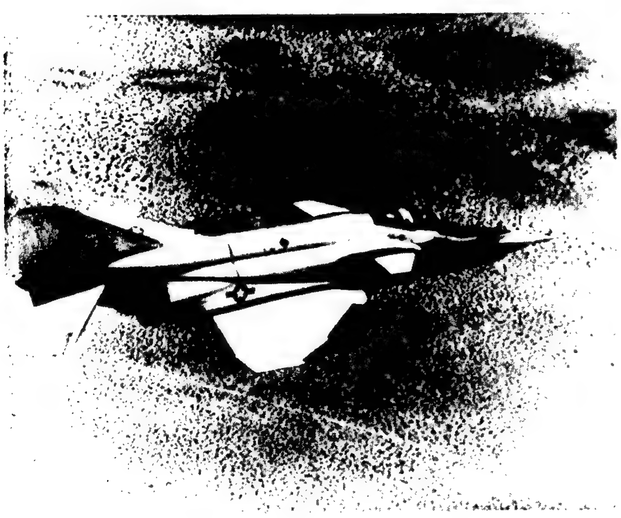


Top view of F-4 fly-by-wire test vehicle, showing the extra canards.

This B-47 was the first aircraft to successfully demonstrate a fly-by-wire flight control system.

This "fly-by-wire" technology was stoutly resisted by engineers and pilots until its safety was fully proved. Triple redundancy (three separate channels providing data) was built into early FBW systems, as a backup against failure. Fly-by-wire was first demonstrated by a Lab program in an F-4 fighter.

In 1967 a Fly-By-Wire Development Facility was set up, and it later became a key element in the Flight Control Division's work. The facility originally had four cockpit simulators to test methods of putting the pilot into the loop.



The F-4 fly-by-wire (FBW) program contributed to the design of an FBW system for the F-16.

Fly-by-wire was first successfully demonstrated in 1967 with a simplex direct electric pitch control system in a B-47. As a result of the B-47 study, a complete fly-by-wire system was designed for an F-4. This three-axis analog system was quad redundant, with full control authority using the advanced control laws developed in the Tactical Weapons Delivery (TWeaD) System program. Finally, the concept was applied to the YF-16, the first aircraft to successfully demonstrate a digital flight control system. In another effort, the Division supported a NASA digital fly-by-wire investigation using the Apollo Lunar Lander computer in an F-8; this program was a forerunner of the Space Shuttle control system. In addition, a simplex integrated actuator package was tested in a YF-4E, and a quadruple-redundant three-axis fly-by-wire system was evaluated. The goal was not only to improve survivability, but also to enhance aiming, tracking and weapon delivery, reduce pilot workload, and achieve weight savings, while permitting greater flexibility in airframe design. No detail was overlooked: the advanced development program (ADP) studied less flammable hydraulic fluids, and methods of eliminating more vulnerable hydraulic lines.

During the Vietnam conflict it was discovered that aircraft were most frequently lost when enemy fire struck these mechanical systems, and the aviation community was forced to admit their vulnerability. The Flight Dynamics Lab led the way in persuading pilots and engineers that redundant FBW systems actually improved safety and survivability, and after the successful F-4 tests Lab engineers began to explore improvements in the concept. A YF-16 was the first aircraft flown entirely without mechanical backup controls. The replacement of analog fly-by-wire circuits by digital flight control technology vastly expanded the capabilities of fly-by-wire systems. Analog systems could entirely replace cables, but digital circuits were flexible enough to accommodate integration with many other aircraft systems. The Integrated Fire/Flight Control (IFFC) project described

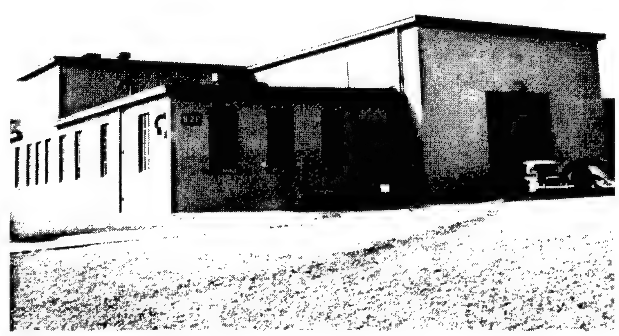
below justified this expectation. Digital flight control systems were flown on the AFTI/F-16, the STOL/MTD F-15 and the X-29 experimental plane. These programs are described in the chapter on Advanced Development. The next step -- under way in the late eighties at the Flight Dynamics Lab -- is "multi-ship integration," the linking of more than one aircraft for targeting and weapon delivery by a single integrated fire/flight control system. During the summer of 1988 the new concept was successfully demonstrated using the AFTI/F-16 and an Army helicopter. The helicopter identifies the target, and automatically transmits bombing coordinates to the fighter plane, which then delivers weapons to the target even when visibility is zero and the flight path is curved. This project is expected to expand into new realms of fighter battle management.

Stability and Control

Characteristics which cause an aircraft to resist changes in its flight path vector are called stability factors, and control is the process of deliberately making those changes. Though some early aircraft designers hoped to achieve inherent stability, such a thing is simply not possible: the stability of a vehicle's path must be constantly adjusted by a human or automatic pilot, through a process known as feedback. Improving stability and control can result in an expanded flight spectrum and also requires configuration changes in aerodynamics, mass/inertia (the weight of the aircraft and its distribution), and structural flexibility.

Stability and control research has always been a relatively small part of the Lab's budget, but significant contributions have been made since World War II. The Aerodynamics Branch of the Aircraft Lab had responsibility for stability and control as well as handling qualities and control analysis before they were transferred to Flight Control in the mid-fifties. A basic textbook on this subject, *Airplane Performance Stability and Control* by Courtland Perkins and Robert E. Hage, was founded on a project in the Aero Branch of the Aircraft Laboratory in the late forties, which in turn drew upon wartime research. Though more extensive stability and control work was being done elsewhere, the Laboratory made significant contributions to the understanding and practical applications of stability and control. For example, the practicality of measuring dynamic stability derivatives in wind tunnels was first demonstrated by the Lab. NACA and other aerospace research teams made extensive use of this technology.

Aeroelasticity (the dynamic interaction of structural stiffness, aerodynamic loads and mass) can be a major factor in stability and control, but analysis of its effects is difficult and complex. Flexible aircraft such as the B-47 prompted the Laboratory to develop adequate analysis techniques to make this problem manageable. A definitive textbook on aircraft aeroelastic effects (*Aeroelasticity in Stability and Control*, WADC-TR-55-173) came out of the Lab's



Supersonic Gasdynamics Facility.

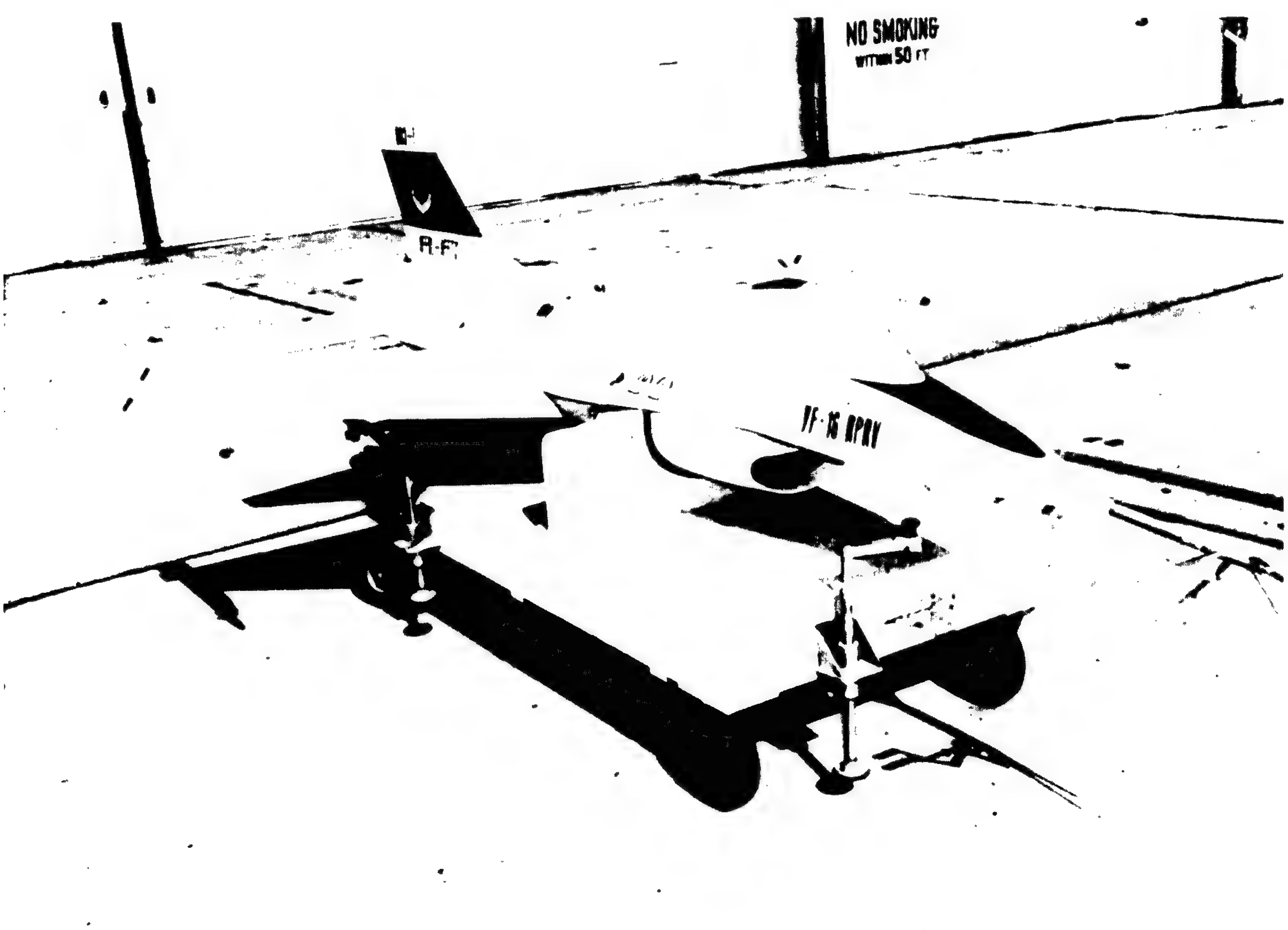
contributions to the Atlas missile program and from tests on the B-36 and B-47. Among the test facilities used were Langley wind tunnels for measuring flight loads and flight control parameters of elastic supersonic and hypersonic aircraft. The Lab was the Air Force leader in solving the inertial coupling problem as a major cause of loss-of-control accidents in the Century

series fighters, and developed prediction techniques for spin, entry and recovery behavior in conjunction with work conducted by NACA research centers.

After the Flight Dynamics Lab was organized in 1960, stability and control research became the responsibility of the Control Criteria Branch. Its Systems Analysis Group specialized in aircraft dynamic analysis, translating mathematical theories into engineering terms. This group collected data and formulated criteria; studied cause/effect relationships; and demonstrated new techniques. In the mid-sixties the group was working on an integrated flight control design emphasizing safety, including an optimum degree of redundancy.

The Aerodynamic Stability and Control Group conducted analytical and wind tunnel tests for dynamic stability, aerothermoelastic effects, hypersonic control, and V/STOL stability and control. In particular, the widely used Datcom computer program was developed as an extension of the published USAF Stability and Control Handbook. The group collected and published data for use by government and industry, as did every other unit in the Lab. Jet interference effects were also being studied at the Supersonic Gasdynamics Facility.

Aircraft stability and control research during the sixties included an advanced development program on nonlinear stall, post-stall, departure and spin characteristics that frequently troubled



YF-16 remotely piloted vehicle subscale model, used to test flight control characteristics of the YF-16 aircraft.

fighter aircraft. A remotely piloted YF-16 drop model was used to study augmentation of stability and control flight testing in hazardous flight regimes. This work led into supermaneuverability research.

The Stability and Control Group was also responsible for developing prediction techniques for the separation of stores from aircraft. This area was transferred to the Aeromechanics Division in the 1970s.

The development of control theory was another ongoing contribution of the Flight Control Lab and its successor division. In the early days theory and practice were rarely coordinated, and much effort was wasted on trial and error experimentation. In the 1930s electrical engineers at Wright Field began exploring the new feedback theory, which gradually replaced the rule-of-thumb in related aspects of flight control. When hydraulic systems were introduced, feedback theory was more widely applied; and when computers came along control theory came into its own. Among other factors, control theory allowed for precise prediction of "robustness," the degree of uncertainty which can safely be tolerated in aircraft stability. Until recent years robustness was predictable as gain and phase margin for only one degree of freedom.

In the 1960s flight control analysts devoted an increasing amount of time to the creation and publication of computer programs such as Datcom, Digital Datcom, and FLEXSTAB. In 1965 the National Aeronautics and Space Administration initiated the development of computer programs to predict the stability and control characteristics of elastic aircraft in the subsonic and transonic regimes. In 1966, Dr. Robert Swaim won the FDL's first Foulois award for his work in developing aeroelastic analysis methods. In 1972 the Flight Dynamics Laboratory took over the new FLEXSTAB program from NASA and extended it to cover conventional and CCV flight control system problems. Cheaper and more efficient computer codes was developed during the 1970s to replace FLEXSTAB.

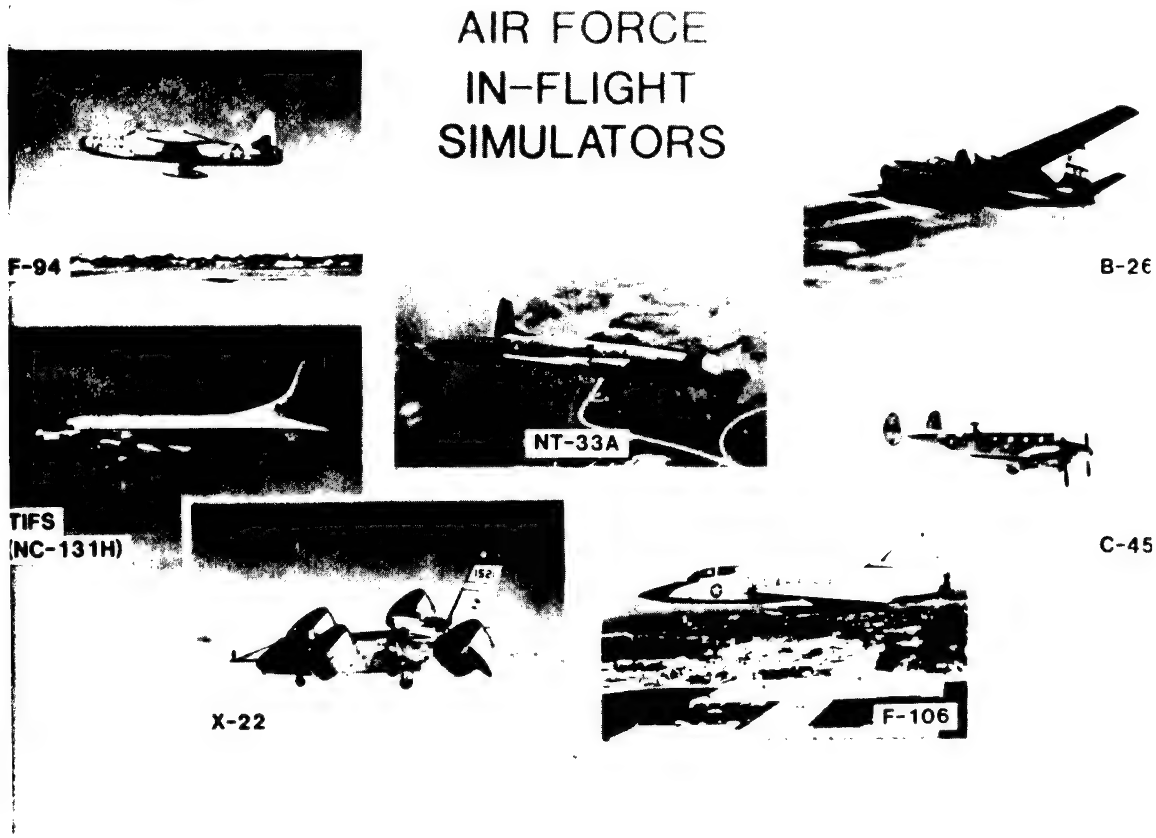
For a time two advanced development programs were concerned with improving flight safety and reducing stall/spin problems. In the short term, efforts were made to modify controls in order to prevent aircraft from surpassing stall/departure boundaries. Eventually the program would recommend design changes to extend the stall/departure boundary. "Spins and post-stall gyrations have been recognized as major problems since the first days of flight," wrote a Lab historian, "so the present state is an indication of the difficulty of the problem." Both the Navy and NASA supported this effort; testing was conducted with the Air Force Flight Test Center's A-7D spin demonstration airplane.

Trajectory analysis

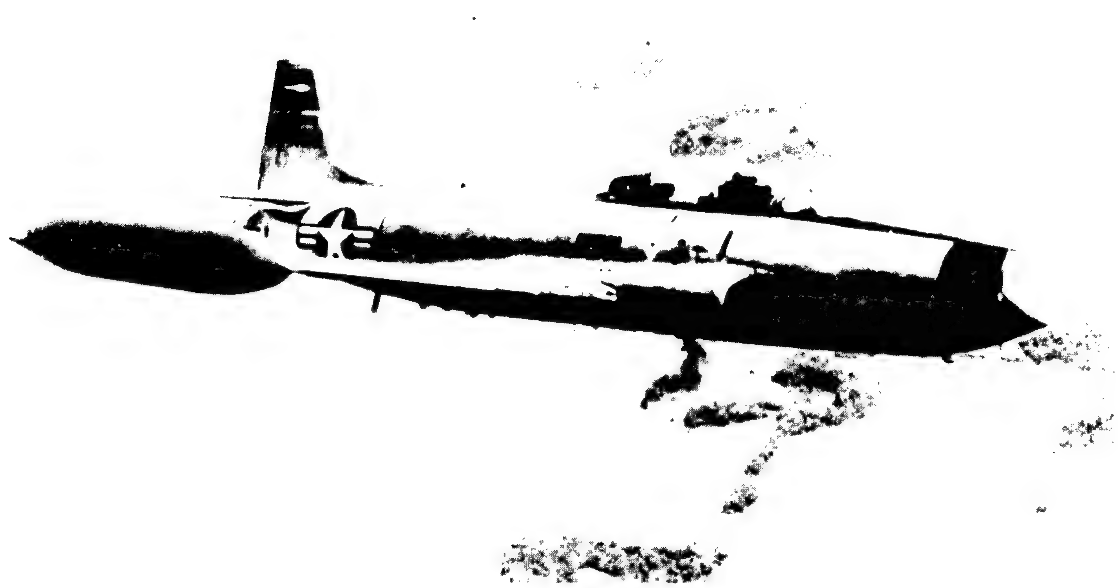
The development of the X-15 experimental aircraft in the late 1950s produced a number of new technologies and revealed unexpected needs. Trajectory analysis, for example, was an important byproduct of the X-15 research. In 1959 the Lab developed the first trajectory analysis computer program for the UNIVAC 1103A, known as "Clay's Program" after its designer. Though very simple, it became the model for all later programs of this type. Also in 1959 a program was created for the IBM 7090 by McDonnell Aircraft, under contract to the Lab; General Electric developed yet another IBM 7090 program for orbital and interplanetary trajectories. All these programs were essential to the progress of the space program in the 1960s.

Flying Qualities

Since World War II the Lab has pursued the study of flying qualities requirements, jointly with the Navy BuWeps, NASA, and the Army. This collaboration has produced since 1943, among other reports, the standard *Flying Qualities of Piloted Airplanes* (1954), and the standard handbook used by the Aeronautical Systems Division. In the mid-fifties, theories of



Some of the in-flight simulators used by Flight Control over the years.



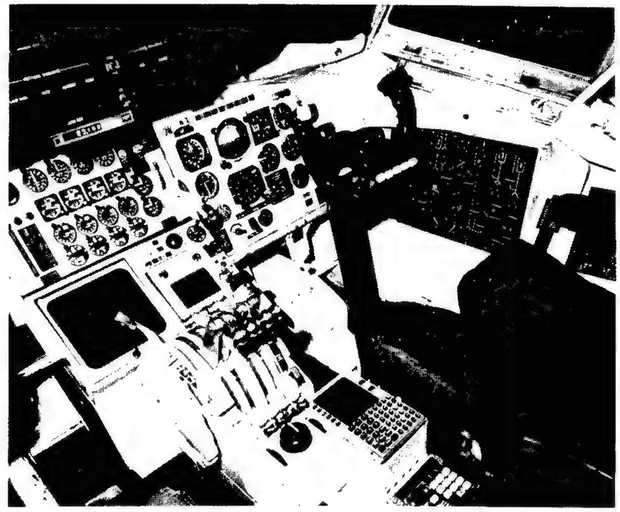
The NT-33 in-flight simulator has the distinguished honor of having the oldest tail number in the active Air Force fleet.

cybernetics emerging from the Aero-Mechanics Branch helped reveal the mechanisms and special problems of pilot/aircraft interaction. Pioneering work sponsored by the Branch combined classical servo theory with physiology to analyze pilot-vehicle behavior. Such "paper pilot" analyses became widely used to develop flying qualities requirements and to investigate specific problems of many varieties of vehicles. For example, a study in the late sixties of accidents involving the T-38 led to ways of correcting pilot-induced oscillations, and the effect of

The NC-131H Total In-Flight Simulator (TIFS) can simulate many aircraft by using extra control surfaces and an on-board flight computer. The test pilot sits under the lower canopy.

longitudinal dynamics on Navy pilots' selection of carrier approach speeds was documented. The Flying Qualities Group improved the design of the highly successful variable stability NT-33 simulator, and many aircraft such as the X-15 and C-5. These variable stability aircraft have contributed extensively to the evolution of flying qualities requirements, among other flight control technologies.

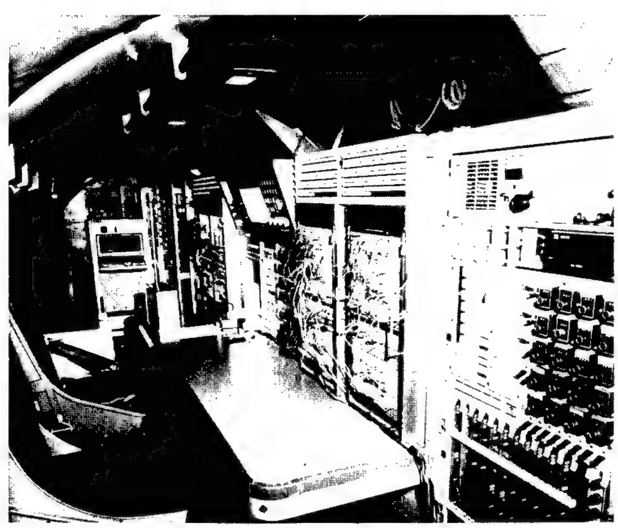
During the sixties the Handling Qualities Group of the Control Criteria Branch conducted human-response testing both in aircraft and the NC-131 Total In-Flight Simulator (TIFS), and



Safety Pilot cockpit in the TIFS.

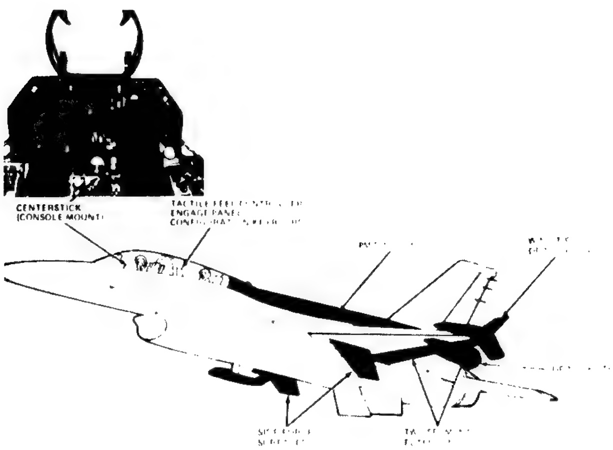
created a mathematical model for the integration of handling qualities factors into the design of flight control systems. The TIFS, which adapted an NC-131 to simulate flying qualities of a wide variety of aircraft, later became one of FDL's most important facilities and is still in 1988 an international flight control resource.

During the past two decades a wide array of new theories, techniques and equipment has revolutionized our understanding of control dynamics analysis. The practical application of this research has produced control equipment and



By altering the gains on the TIFS in-flight computer, the NC-131H can duplicate the flight characteristics of many different aircraft.

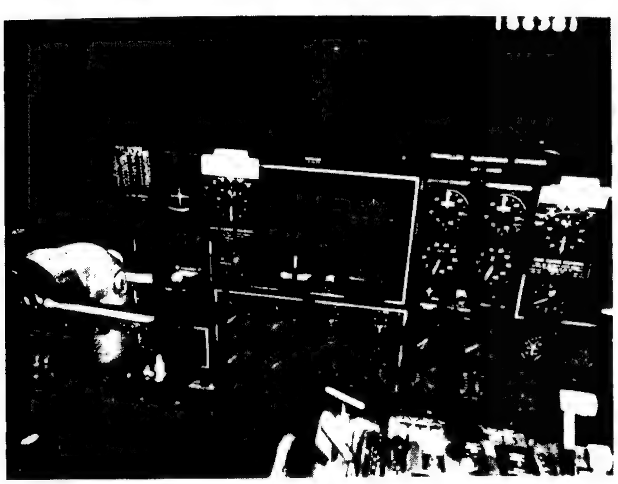
instrumentation that, not long ago, could be found only in science fiction.



The VISTA, a highly modified F-16D aircraft, will soon replace the NT-33 in-flight simulator.

Control Equipment

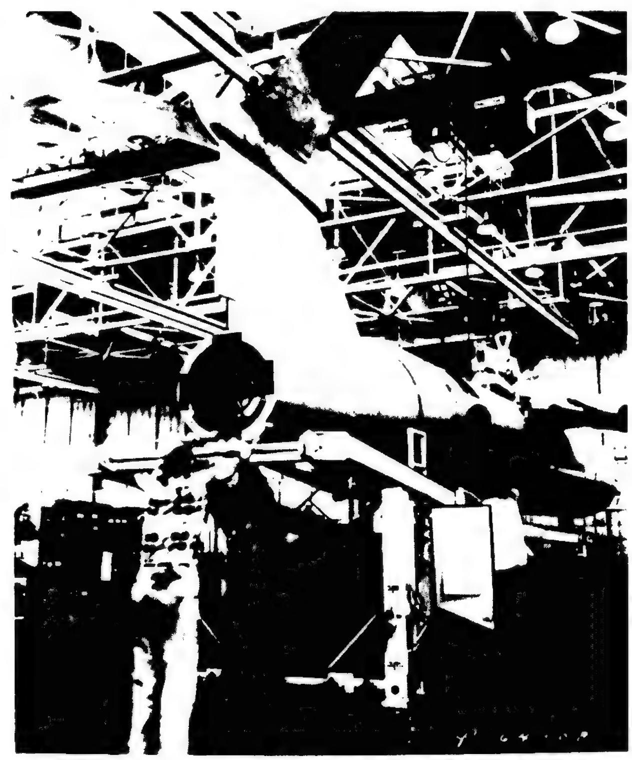
During the five years following World War II the Equipment Lab and its contractors produced a wide range of autopilots for most aircraft then in use. This technology was important in the development of remotely piloted vehicles and drones, such as those used to gather data near atomic bomb test sites. A major contribution of this research was the development of approach



1945 cockpit with an early autopilot.

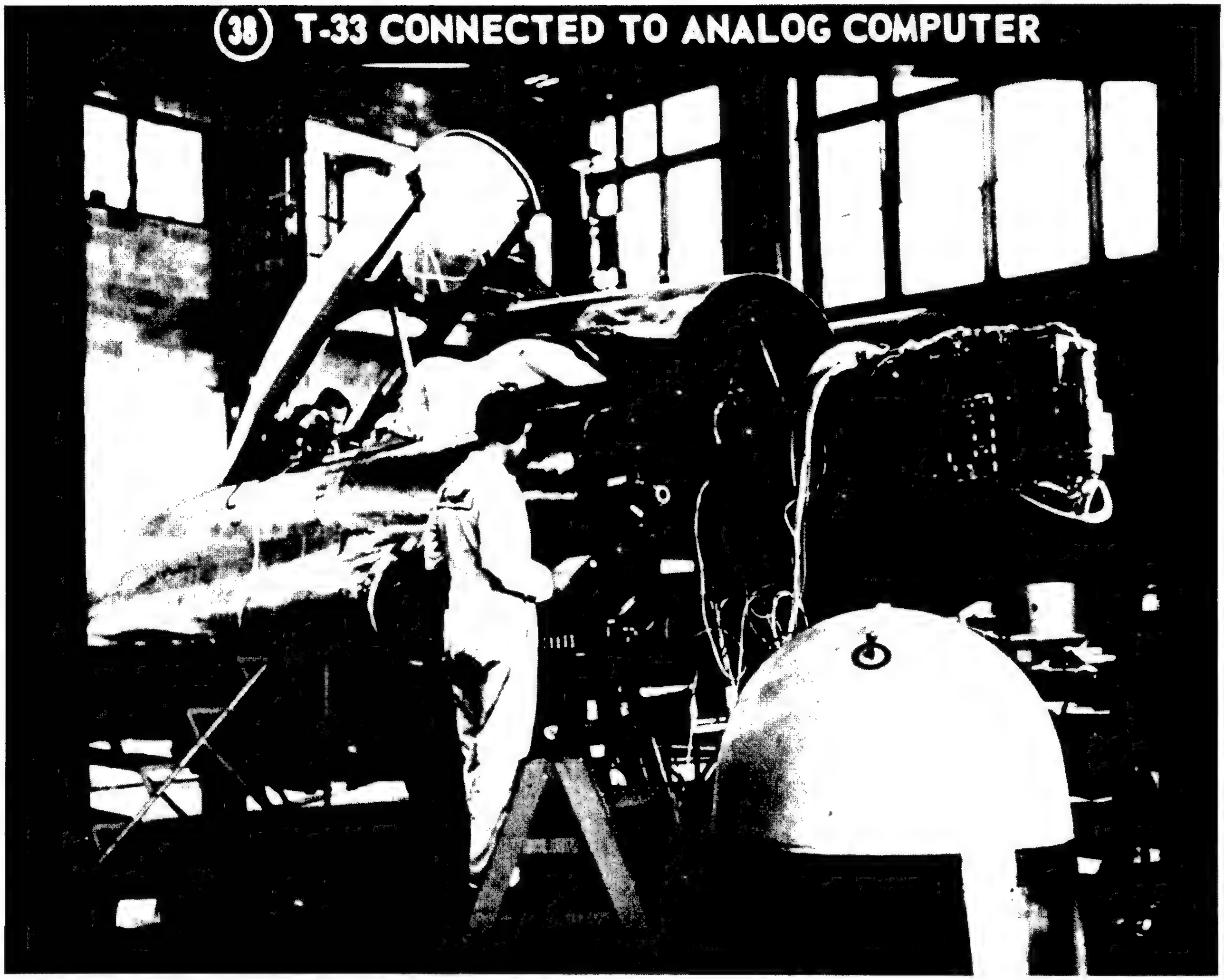
couplers and flight directors for all-weather capability.

In the early 1950s most Air Force missiles used some variety of the autopilots developed for the Lab. These included the Snark, Matador, Rascal, and Navaho. Autopilots were also modified for fire control and bombing concepts. Before that time autopilots were regarded as accessory to pilot control, and capable of override. The Lab pioneered the radical new concept of integrating the pilot into the automatic control loop. The first step in this process was a control wheel steering concept which gave the pilot more accurate manual maneuvering capability.



Technicians working on a Matador missile before testing.

In 1955 it was believed that the limits of conventional autopilot technology had been reached, and therefore work began on self-adaptive control systems such as the one eventually tested in the X-15, permitting that aircraft to exceed its design altitude. The theoretical and practical applications of this



T-33 used to test a flight control analog computer in 1956.

radically new concept have been far-reaching. The Control Augmentation System (CAS), for example, simplified control system designs by eliminating complex mechanical devices. Self-adaptive controls, which are now commonplace, use servomechanical feedback devices to correct the autopilot's course, in response to changes in configuration and environment.

As automatic control systems became more sophisticated, taking over a greater portion of aircraft operation, redundancies were built into the systems to ensure safety and reliability. Multiple channels and monitor channels were developed. Two channels were not enough; if two instruments gave different readings, the pilot could not know which was correct. Three could break the tie vote. Four channels were better still, but at the cost of prohibitive weight and power consumption penalties and maintenance difficulties. In the late fifties research began on "fail operational" reliability techniques which were eventually incorporated into many aircraft and even the Apollo guidance system. This permits the control system to continue operating if some of the channels fail. Numerous

improvements have since been made in redundant design techniques that assure increased reliability without excessive weight and power penalties.

Spinoffs from control equipment research have been numerous. As early as 1950 the Lab was using a primitive analog computer to develop comprehensive simulation and prediction methods, taking into account nonlinearities which had proved intractable in pre-computer days. Today's extensive use of computers for flight dynamics research grew out of this original project.

With the establishment of the Flight Dynamics Lab in 1963, control equipment research became the responsibility of the Control Elements Branch. Servomechanism and feedback theory, control problem synthesis, controllers and actuators, and composite data systems were among the Branch's research priorities. Technologies under investigation included improved reliability of control systems, especially during unattended periods. Control for spacecraft was a new field in the early sixties: engineers were working in particular on concepts for spacecraft attitude control. The lab also contributed to the X-15 self-adaptive control system and developed a hot-gas flight control system for extreme temperature and high radiation environments. The all-attitude inertial flight data system for the X-15 included new stable-platform concepts, and was ready for testing in November 1958. Three X-15s eventually flew, and provided data for further flight control research. The first adaptive control system, reaction controls for attitude control in space, and the Gyroscopic Low-Power Attitude Control System for satellite applications grew out of this work.

Transducers and single-and multi-axis redundant rate and acceleration sensors were also under investigation, and contributed to several new projects, including the Tactical Weapon Delivery System (TWeaD), tested in an F-4C. TWeaD expanded the control deflection authority of the stability augmentation system

The Flight Control Lab developed the all-attitude inertial flight data system for the X-15 experimental aircraft.

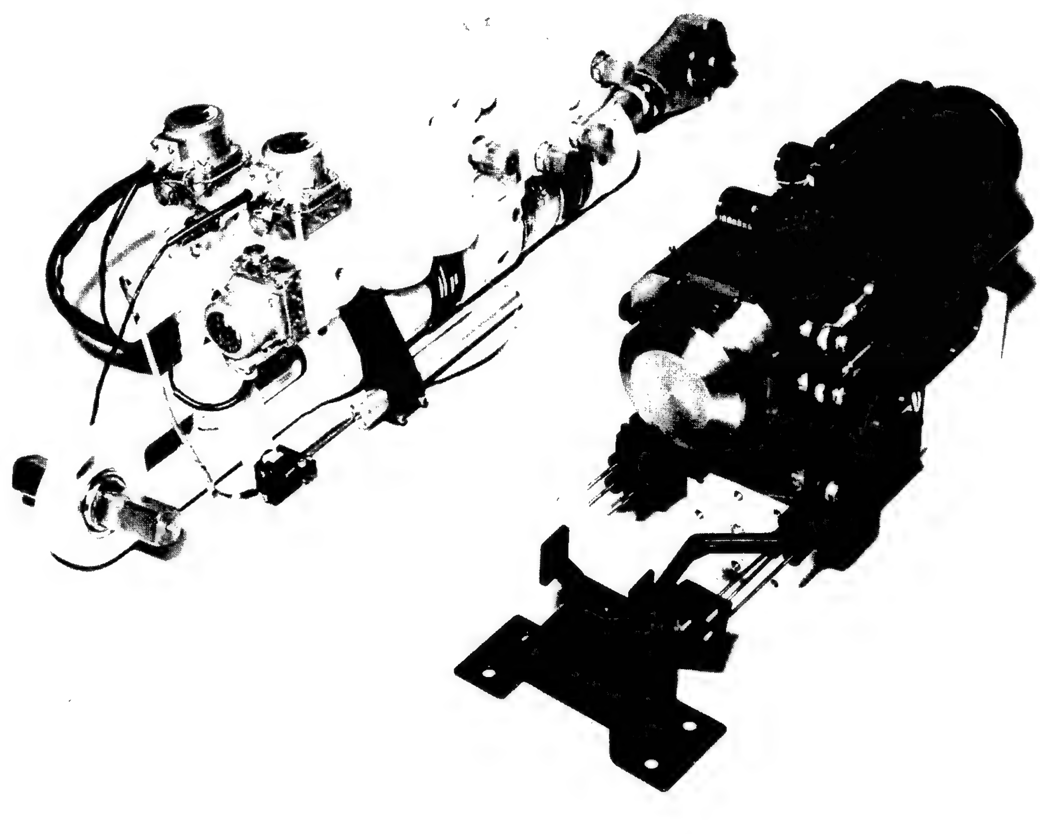
and provided greater maneuvering precision for weapon delivery and enemy antiaircraft fire avoidance. The Branch also created the Advanced Flight Reference Stabilization System, which used a miniaturized inertial measurement unit to provide data commands to the cockpit display and other aircraft systems. The whole unit weighed less than thirteen pounds, and was an early miracle of miniaturization techniques; the concept contributed to later fly-by-wire developments. A team headed by Max Lipscomb developed the flight control sensors which made the miniaturization possible. In addition, the Branch developed a Nuclear Magnetic Resonance Flowmeter to measure propellant use rate in turbines and rocket engines.

A hydrofluidic yaw stability augmentation system and redundancy schemes for hydraulic servoactuators were among the projects under way in the mid-seventies. A pitch-axis test rig had been built for evaluating the latter project,

and a Digital Multi-Mode Control Acquisition System was being tested in the A-7D vehicle.

Later in the seventies there was a trend toward more extensive use of computers and more careful study of problems of integration with other aircraft systems. The Control Systems Development Branch now emphasized redundancy techniques for safety, as well as cost reduction. Facilities in use included an instrument development lab, fabrication equipment, a hydraulics servoactuation lab, a digital avionic flight control integration lab, and a cold gas plasma tunnel.

Actuator research has continued into the late 1980s. An integrated left-hand servoactuator for an F-16 was developed to simplify the signal hydraulically and to provide control output. A right-hand actuator with direct-drive valve amplifies the input signal electrically to provide control output. Both devices are simpler and less expensive than earlier actuators. The technology has been transferred to the F-15 stability servoactuator and also to the Swedish JAS39 "Gripen." An electromechanical actuator for the C-141 aileron was recently developed under contract at Lockheed, built at Sundstrand, and



The electromechanical actuator on the right is much more reliable than the hydraulic actuator on the left.

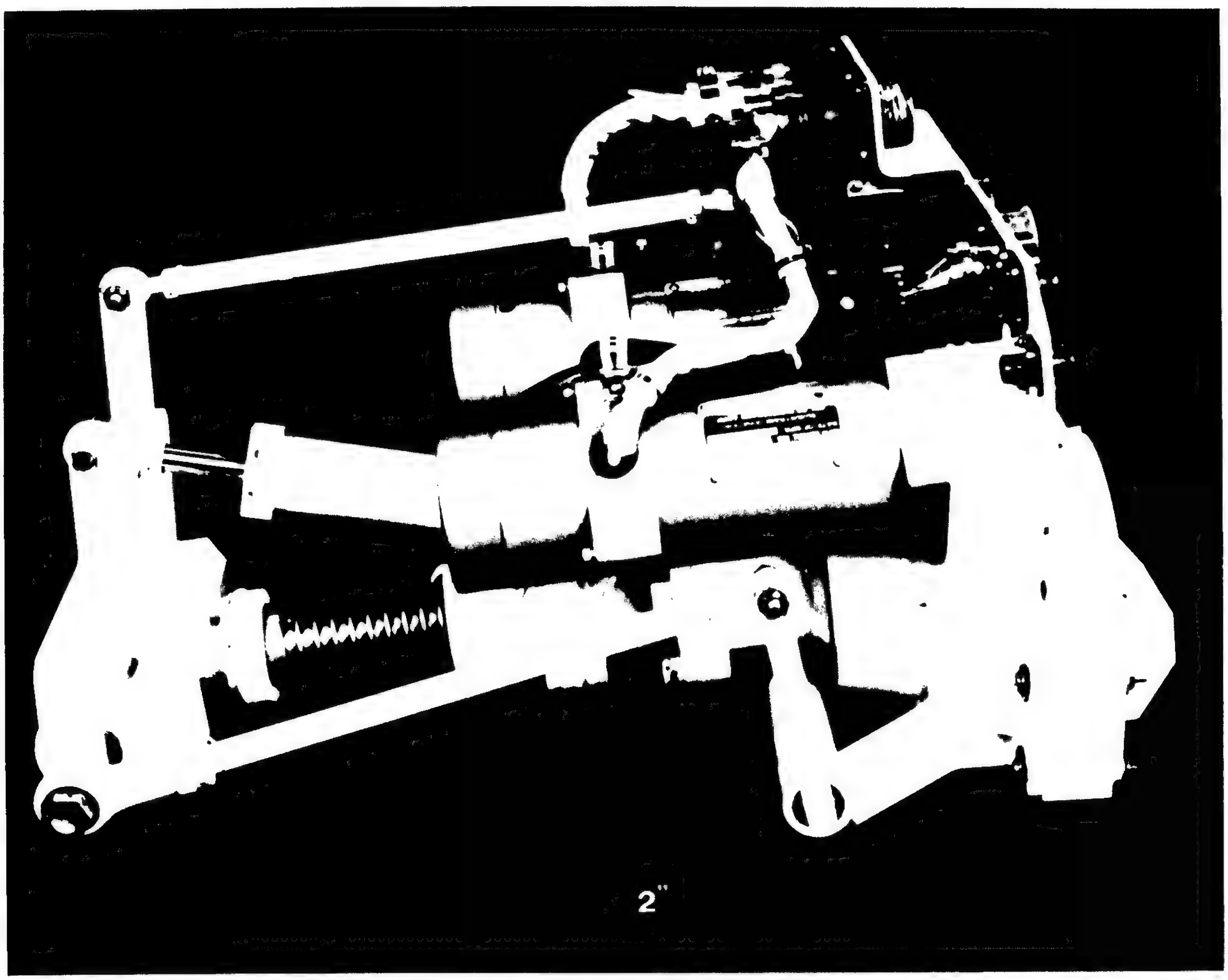
then flight-tested by the 4950th test wing at WPAFB.

A plastic molded actuator for fin control in the Maverick missile was another recent product of the Division.

By the late sixties the Control Elements Branch had made considerable progress on hot-gas control systems, expanding knowledge of fluid dynamics under extreme conditions and developing a system capable of operating reliably at 1400F. The self-organizing flight controller developed at the branch was the first successful use of bionic techniques. Data acquisition research resulted in smaller and lighter systems; a hypersonic air data probe was tested, and propulsion and propellant instruments were designed capable of withstanding temperatures up to 1000 degrees Centigrade.

The use of fiber optics for control signal transmission was demonstrated successfully in 1980. Fiber optics are less susceptible to signal shorting, lightning and other electrical disturbances, and can carry more data than electrical wires.

A modified A-7D, flying out of Edwards AFB, proved the feasibility of this aspect of Digital Tactical aircraft control (DIGITAC) technology. The new concept was nicknamed "fly-by-light,"

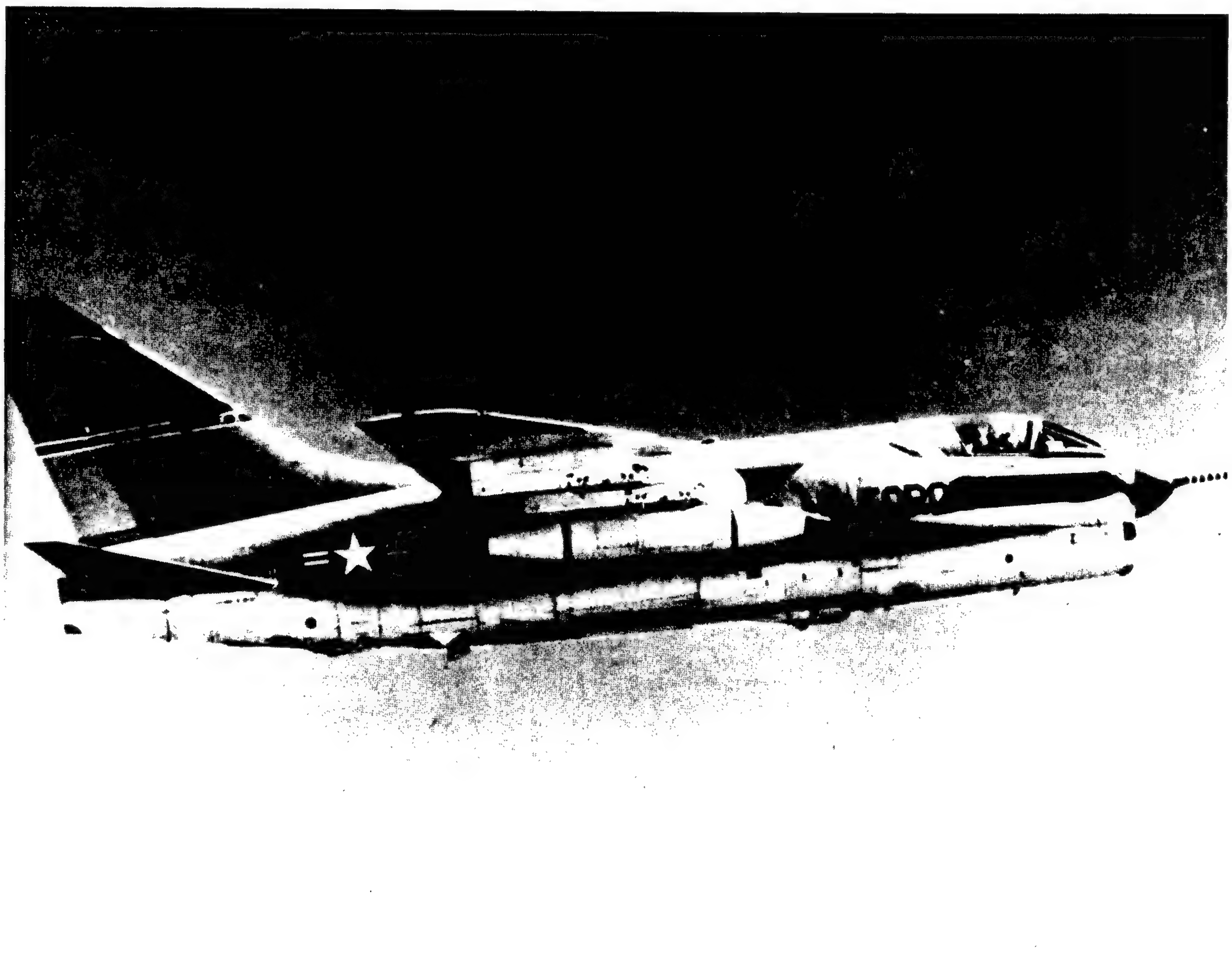


Electromechanical actuator tested on a C-141 edge flap.

Missile-sized control surface actuator using molded plastic parts for lower production costs.

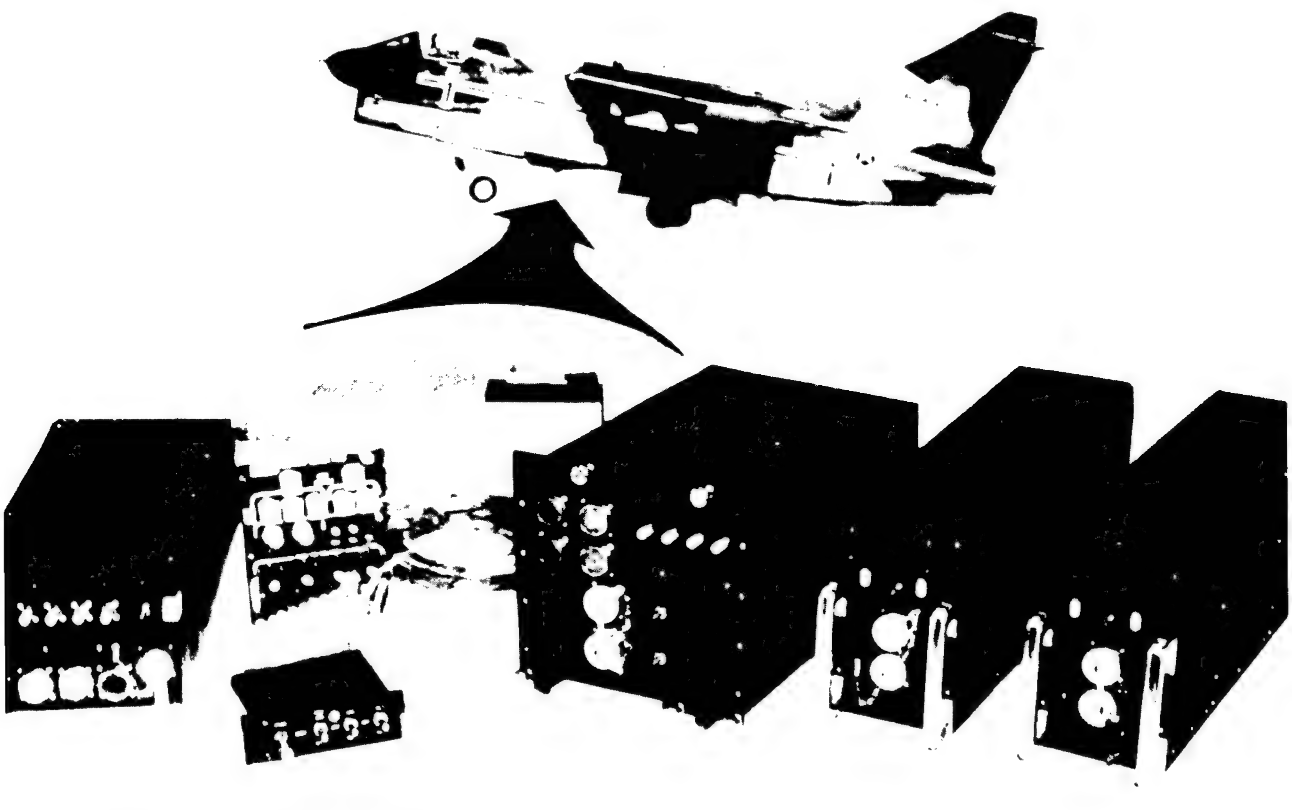
since it was seen as a successor to the "fly-by-wire" technology developed at the Lab in the sixties.

During 1982 the Lab developed a single fiber optic multiplex system, to replace the original fiber bundles. The dual digital data bus system installed in the DIGITAC A-7D aircraft consisted of forward and midship remote terminal units and a Bus Controller/Interface Unit for each of the data bus channels. Flight data were fed to the flight control computer entirely through this fly-by-light system. The multiplex system was designed for easy detection of failures, as well as for greater reliability and survivability and lower cost and weight. By the end of 1982 the A-7D

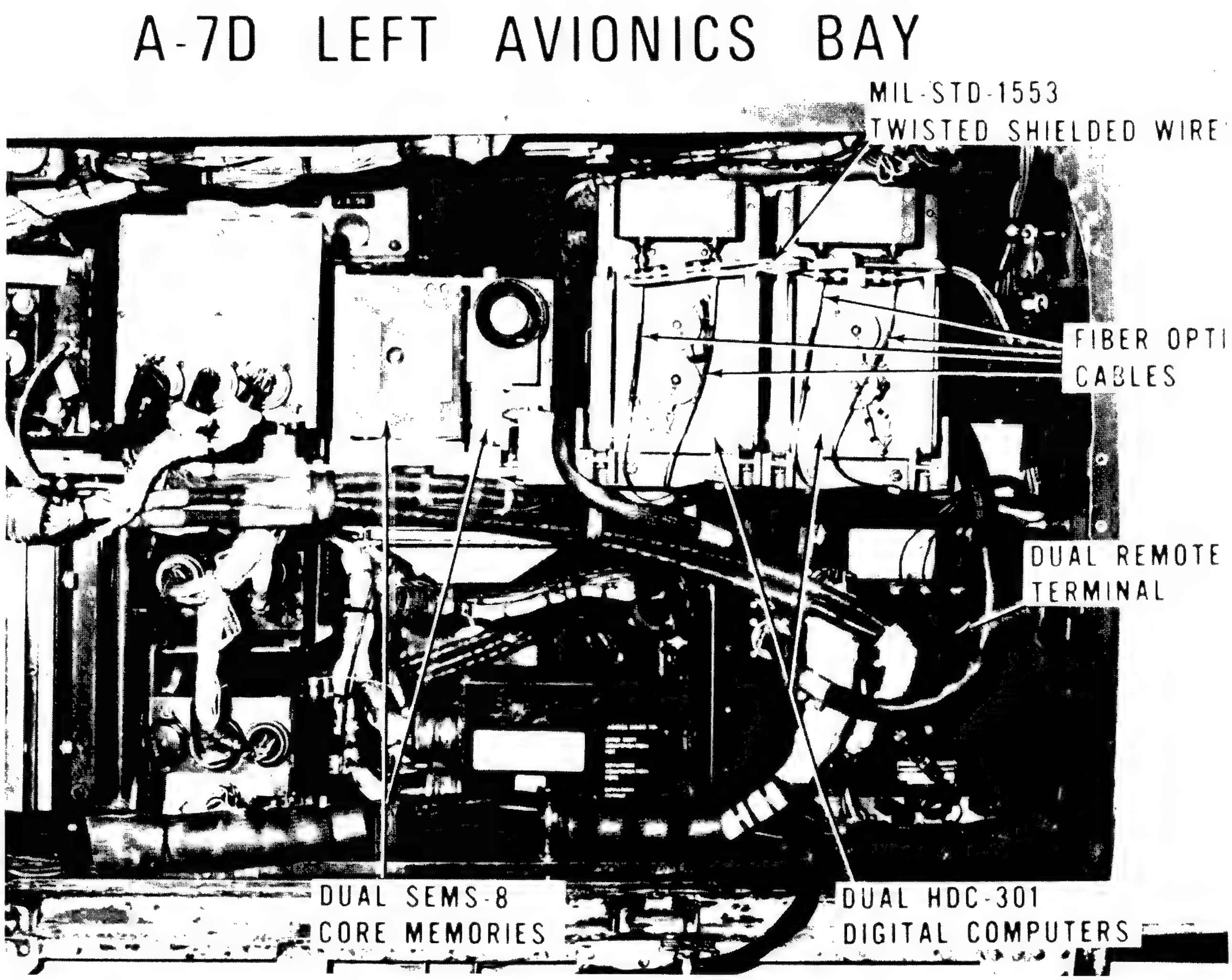


This A-7D demonstrated DIGITAC technology.

The A-7D DIGITAC aircraft used a fly-by-light fiber optic control system, an advance over FBW.



Some of the A-7D DIGITAC "black boxes."

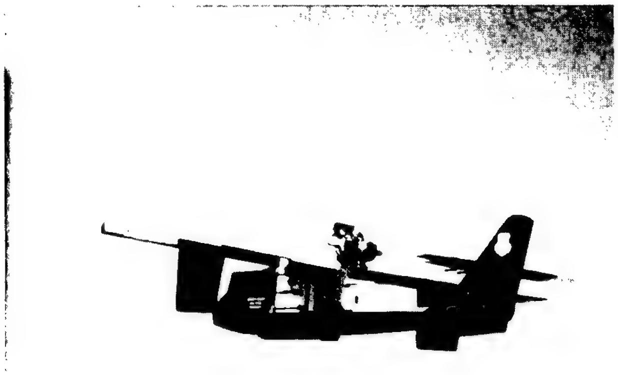


The equipment bay of the A-7D fly-by-light demonstrator shows some of the complexity of modern flight control systems.

test aircraft had completed 109 successful flights. Not one failure occurred.

In another project, the Flight Control Division began work in 1981 on a Continuously Reconfiguring Multi-Microprocessor Flight Control System. The concept, which was expected to result in cost savings, involved the dynamic redistribution of tasks among multiple microprocessors in a continuing process of reconfiguration. Continuous spare checkout, latent fault protection, and elimination of failure transients are some benefits of this approach. Most important, the system is highly flexible and can accommodate most changes in system design without the unwanted propagation of other changes and their attendant costs. Not surprisingly, the "CRM2FCS" proved to be a major technological advance.

Development and flight testing of a low-cost autopilot for an unmanned research vehicle were also accomplished in the early eighties. Microprocessor chips commercially available from the automotive industry were adapted for a missile flight control system costing less than $50,000. Five successful flight tests have been conducted since October 1983 using an XBQM-106 vehicle. This research is continuing at the Division under the Unmanned Aerial Vehicles (UAV) program. A range of UAVs is under development for applications as low-cost test beds for high risk tests of fault detection and system reconfiguration concepts.

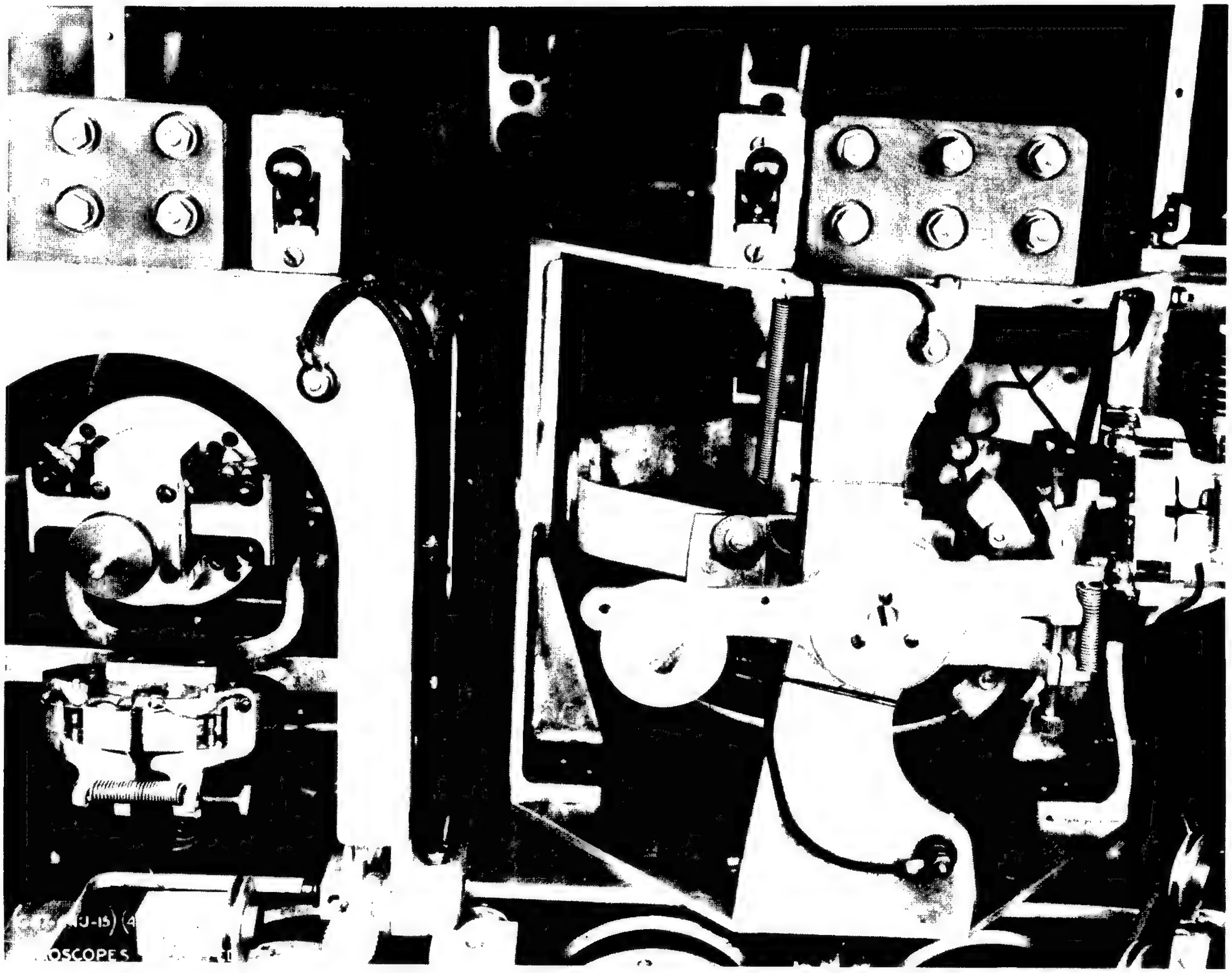


Remotely piloted vehicle used to test a self-repairing flight control system. The test was considered too dangerous to use a human pilot.

Control Instrumentation

Experimentation with attitude reference instruments began as early as 1918, when the Sperry Corporation first studied gyroscopic instrumentation. The laboratories at McCook Field soon assumed leadership in this field, and research was transferred to Wright Field in 1927. Flight indicators and directional gyros were developed in 1930-31 for flying air mail in poor visibility conditions. These instruments were improved considerably in the late 1930s, and at the outbreak of World War II existing fighter aircraft were retrofitted. These primitive gyros greatly increased the operating parameters of fighter planes, but they were air-driven and susceptible to frequent breakdowns. Air contamination and pressure changes made the

Technicians working on a low-cost RPV.



An Airplane Lab photo from the 1930s showing a typical gyroscope.

instruments unreliable, and during the war the Lab placed high priority on developing electrical gyros. Improvements were spectacular but the new gyros were still inadequate, especially for the jet aircraft then coming into service. They were susceptible to high drift; they were heavy, and had an unacceptable failure rate.

Between 1945 and 1950 the lab developed advanced gyroscopic controls and servo indicators for heading and altitude measurement. The flight director, originally called a Zero-reader, was critical for instrument landing systems. Greater versatility was achieved, and interconnections were simplified. An indicator combining altitude and direction was developed, and variations on this concept became standard on all aircraft in the fifties and sixties. A three-axis indicator was also designed for the X-15 and later adapted for manned space vehicles. During this same period multi-gyro, common gimbal control packages were developed, and when combined with altitude/directional instruments, produced a compact, reliable inertial reference unit which served as the central element of an integrated control data system. Perfection of this concept was a prime target of instrumentation research under the new Flight Dynamics Lab. In particular, Max Lipscomb's group aimed at improved miniaturization of control and

guidance systems. In the long run these efforts have been among the Division's most significant contributions.

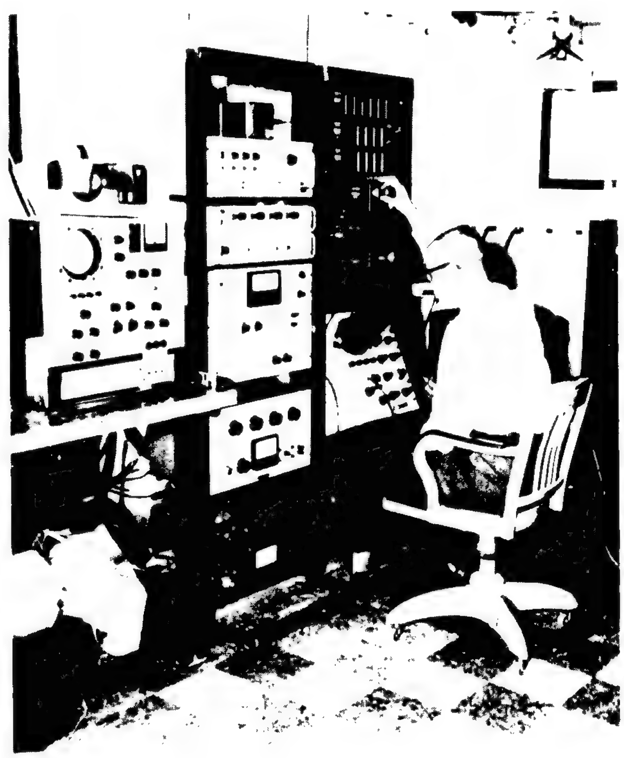
The Control Data Group was responsible for on-board sensing and processing of control data parameters. Newer aircraft required more accurate data references, real time in-flight measurements and better prediction techniques. A special problem was obtaining dependable information from data systems when input was imperfect or incomplete. This group developed air data probes, single- and dual-axis rate sensors, high-temperature pressure sensors, and other high-temperature measuring devices.

In the mid-sixties research was begun into an area which would later prove highly significant: the application of radioisotopes and X-rays as sensors for altitude, fuel flow, and velocity measurements.

Much of the early control research was conducted at the Instrumentation Physics Research Facility, which was established to conduct research on flight control data measurement, especially in the fast-changing realm of nuclear physics. In the mid-sixties work concentrated in three areas: radioisotopes, nuclear magnetic resonance and the Mossbauer effect. The scattering and absorption of radiation

Physics Research Laboratory, Building 79E.

Ion probe used for hypersonic air data measurements.

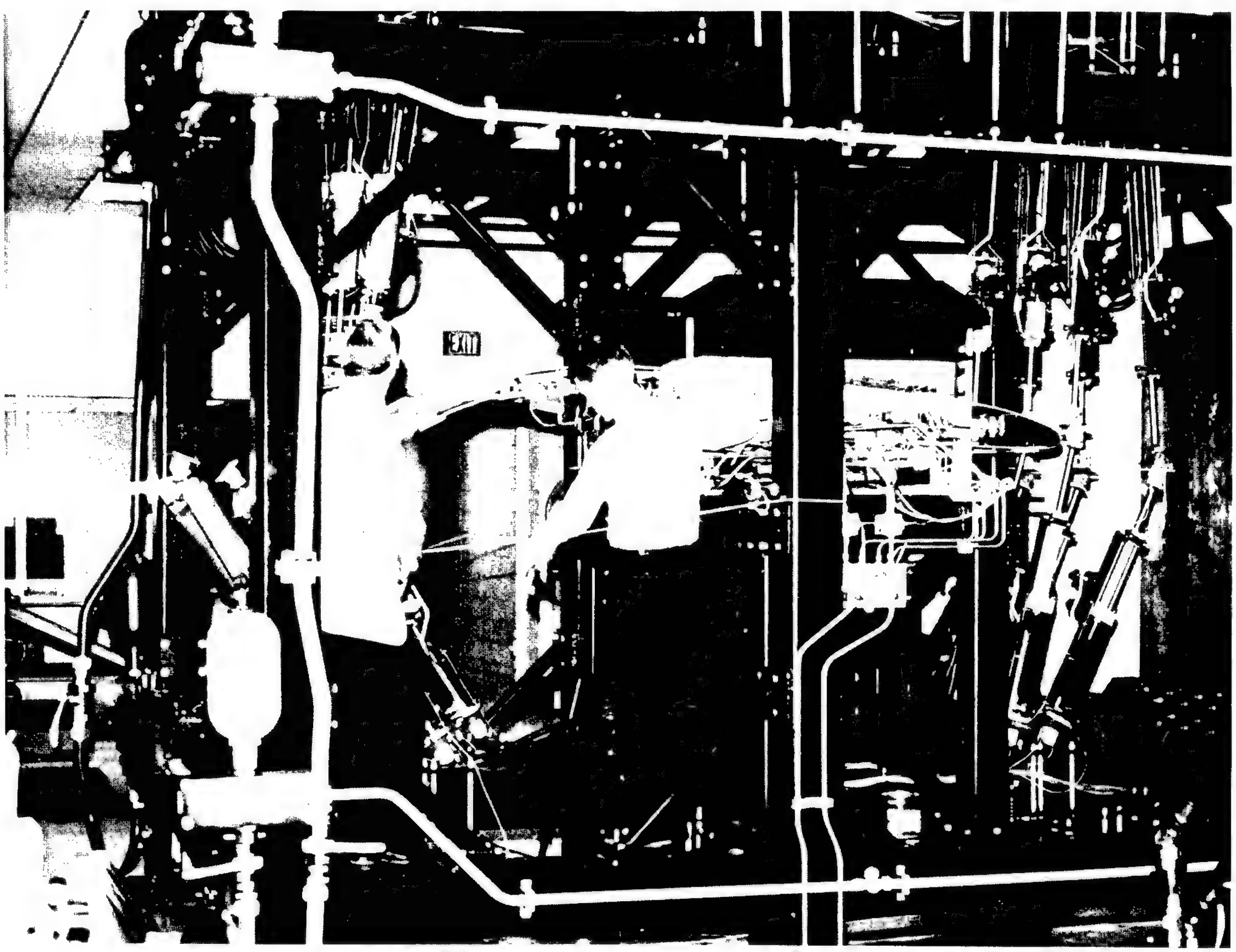


Test operator watching a scope in the control room of the Physics Research Lab.

from isotopes can be used to measure air density, mass fuel quantity in zero-G conditions, and low-altitude parameters for V/STOL aircraft. Magnetic resonance was explored for its potential in measuring mass fuel flow, and the Mossbauer effect has applications in extremely precise position and velocity measurements. In the later sixties tests were conducted on collimation and fringing of radiation beams for landing data. In the early seventies the facility explored nucleonics, solid state technology, plasma and X-rays for other types of data measurement. The facility was largely staffed by Air Force Institute of Technology (AFIT) graduate students and students from local universities.

The current actuator test rig recently conducted dynamic loads testing on the variable camber wing, simulating the effect of typical aerodynamic loads on actuators and sensors.

The Flight Control Systems Techniques Simulation Facility included a plasma physics facility, capable of producing plasmas of densities up to 10^{14} electrons per cubic centimeter. Various diagnostic techniques were used to measure plasma properties in re-entry nose cone studies, exhausts of ion engines, and ionized flow around bodies. Before its demise in 1980 this facility took on a large percentage of the Division's research, and was capable of fully simulating all aspects of flight control in an aerospace vehicle. It could also simulate



Actuator test rig. Aerodynamic loads are applied to an actuated wing section to test the actuator's ability to handle realistic flight loads.

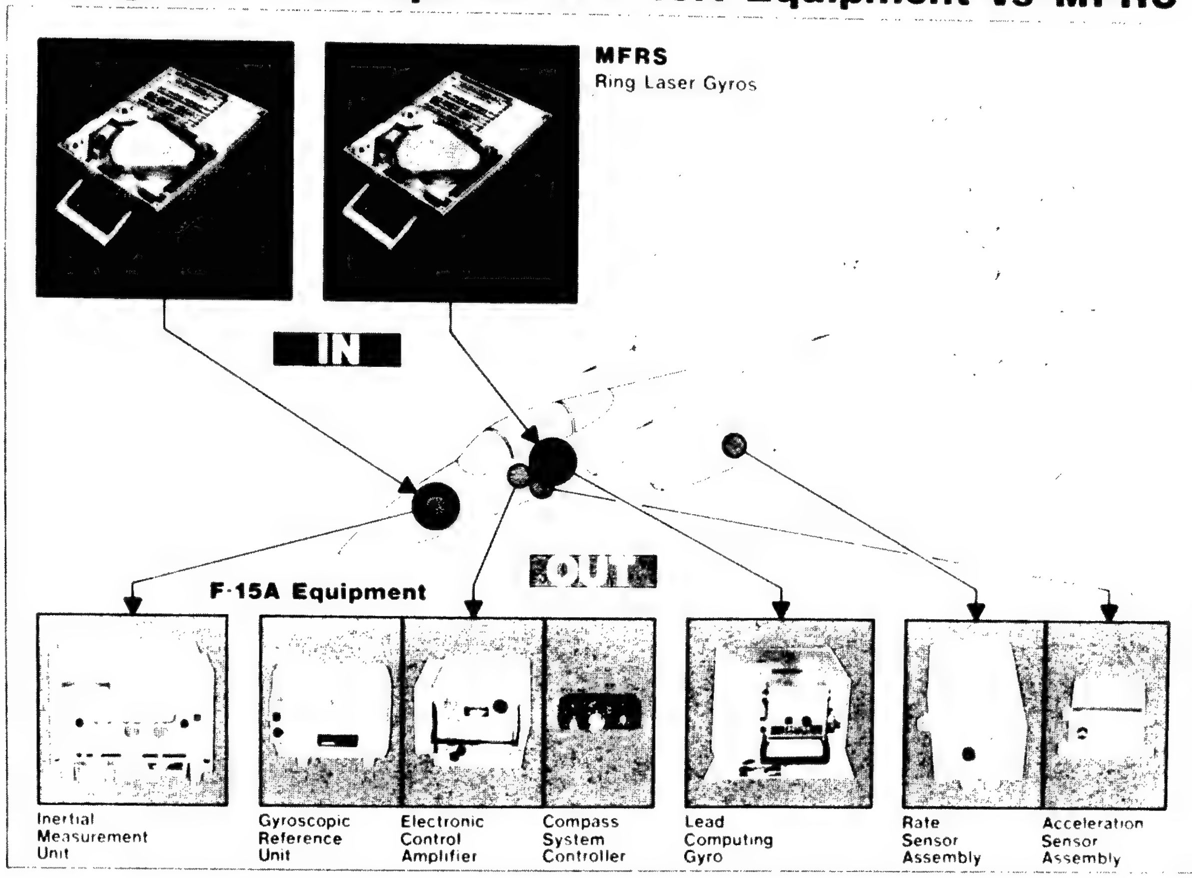
dynamic loads in order to study all types of equipment under various flight conditions. The simulation computer was originally an analog/digital hybrid.

Flight Dynamics Lab research often leads to valuable spinoffs, and the integrated control data system was no exception. These spinoffs included such gyro-based instruments as the coordinate inertial platform used in the Bomarc missile; the two-gyro controls for the F-105 and F-106; and an inertial guidance system used by many Navy aircraft. A Multifunction Flight Reference System (MIRA) concept was explored jointly with the Avionics Laboratory. The idea was to have a single inertia reference system for navigation, guidance, fire control and flight control, thus eliminating some of the redundance reference instrumentation in many aircraft.

A major effort of the 1980s was the Multifunction Flight Control Reference System (MFCRS). The goal was reliable, fault tolerant outputs from a single, onboard multifunction ring laser gyro inertial reference system. Problems of sensor location compensation, redundancy management and flight safety had to be resolved. The system employed six inertial quality ring laser gyros and accelerometers in a redundant, dispersed, skewed axis configuration. Software was successfully developed, and the ring laser gyro was fabricated and tested in an F-15. Tests

Building 434, an early flight control simulator lab.

Multifunction Flight Reference System
Configuration Comparison: F-15A Equipment vs MFRS



The Multifunction Flight Reference System replaced seven boxes in the F-15 with just two boxes. Each box contains four ring laser gyros and associated digital electronics.

indicated a problem with low damping, but demonstrated the feasibility of such a system. It was predicted that high reliability and cost effectiveness could be achieved, and subsequent flight tests have borne this prediction out.

Flight Instrumentation and Air Data Systems

The increasingly sophisticated aircraft of the post-World War II era required entirely new concepts in air data indication. In the earliest aircraft the pilots had to rely on their eyes, ears and intuition. Static and dynamic pressure, airspeed, and temperature could be indicated by very simple instruments. But these were soon inadequate. The Lab's first efforts in the direction of improved instrumentation produced the Machmeter and indicators for equivalent airspeed, true airspeed and true altitude. The World War II experience demonstrated that even more sophisticated instruments were needed, but during and just after the war other areas of research were deemed more important. Not until about 1950 did the lab commence serious work on air data instrumentation.

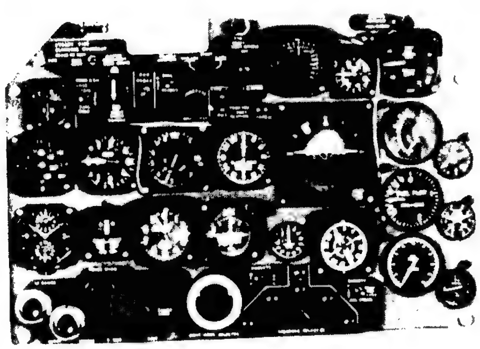
As early as 1952 the lab had designed the first central air data computer; it was installed and tested on a B-52. A more complete system was developed for the F-101 in 1954, and its success led to its further use on the B-58 and C-141. Navy and commercial aircraft soon adopted the same system. This standard air data computer

received four inputs: total pressure, static pressure, free air temperature, and uncorrected angle of attack. Its output included pressure altitude, Mach number, impact pressure, computed airspeed, vertical speed, true airspeed, maximum safe speed, airspeed hold, altitude hold, Mach hold, Mach rate, true angle of attack, true outside air temperature, air density and total temperature. These data were supplied to the fire control, flight control and engine systems; to the cockpit instrumentation; and to the navigator or bomb navigator. For some aircraft the total number of outputs could run as high as seventy, though the typical bomber or fighter required about fifty. The air data computer greatly increased the capabilities of weapon systems and reduced costs and maintenance.

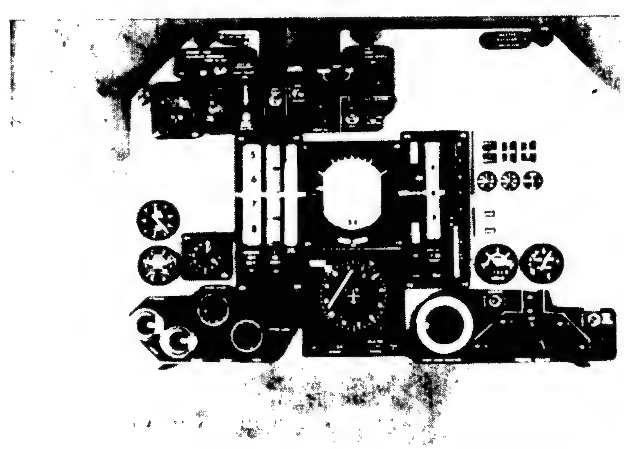
Control Displays

With the development of high-performance and supersonic aircraft in the 1950s came a need for control displays with greater range and accuracy, and better visibility. The Lab decided to scrap the old dashboard-type instrument arrangement and developed the now-familiar "Tee" concept, first applied in the F-105 and F-106. Instruments indicating pitch data were grouped along a horizontal scan line while lateral or directional data were shown on a vertical line so that pilots could now take in a greater range of data at a glance. Vertical scale instrumentation was the first major change in aircraft instrumentation since indicators were first installed in airplanes. Fuel management and engine instrumentation were later added to the Tee display, and first tested in the F-105 and F-106. The new instrument panel was 30% smaller, but displayed more data and conveyed more information quickly to the pilot, than any previous panel. The space savings permitted the location of weapon delivery controls on the main panel. This "whole panel concept" eliminated confusion and contradictory instrument readings. As work continued, the instrument panels became easier to use, more "pilot-friendly." In some cases, several old instruments could be combined into one. For example, the lab designed the standard "horizontal situation display," replacing the former ILS, bearing, heading and distance indicators. Also, the "flight director" superimposed steering needles over the altitude display, making it easier to determine flight paths.

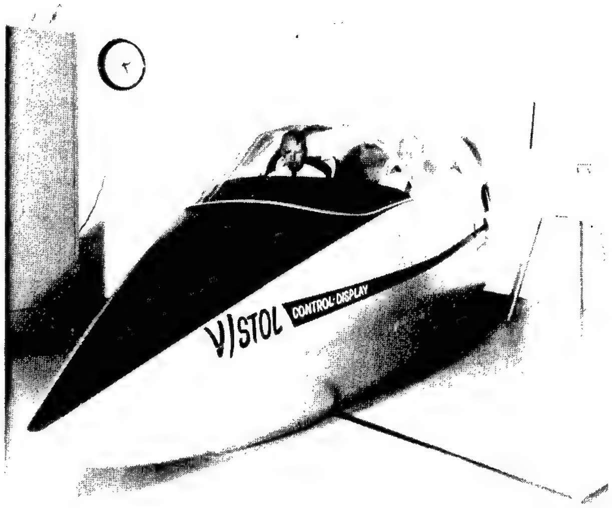
To avoid the possibility of confusion when one instrument relayed several types of data, the Lab designed the mode and function management control panel, coupled with a logic computer which provided the pilot a single point of contact with all flight and navigation subsystems. This concept also quickly became standard in most aircraft, with minor variations for individual needs.



Cockpit display panel showing the numerous dials and gauges of a 1950s-era fighter aircraft.



Cockpit display panel with the easier-to-read "Tee" concept.

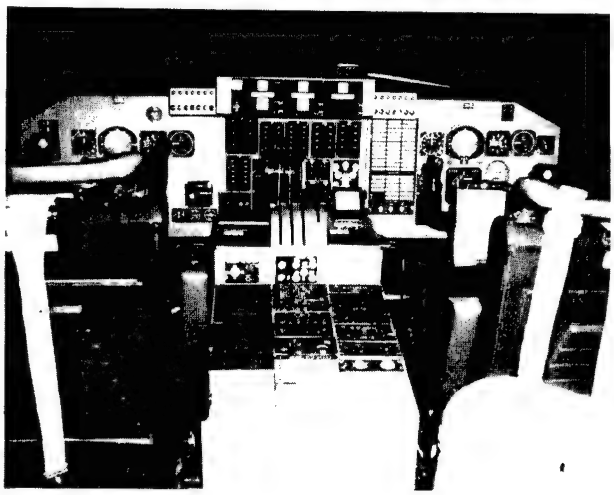


Building 434 housed this early V/STOL instrumentation mockup.

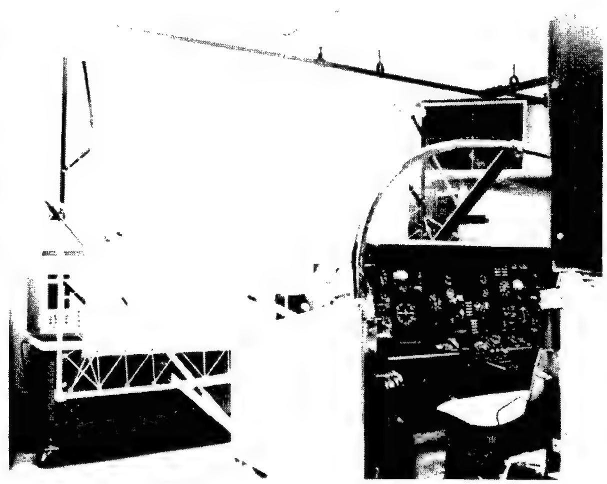
A number of associated developments have improved pilot interaction with the control panel. The Lab created the vertical flight path computer, permitting the pilot to choose a flight path based simultaneously on horizontal and vertical data. The Lab pioneered the development of standby instrumentation and operational flight director computers. The Lab also designed entirely new instrument panels to cope with the special requirements of V/STOL aircraft.

During the 1960s interest shifted to solid-state instrumentation. The first applications of this new technology was the development of electroluminescent panel lighting used in the Apollo and LEM vehicles. This effectively solved the problem of reading instruments in bright ambient light in space or on the lunar surface. A three-axis display (pitch, roll and azimuth) was also developed for the Apollo and Gemini projects, and was used in the F-111.

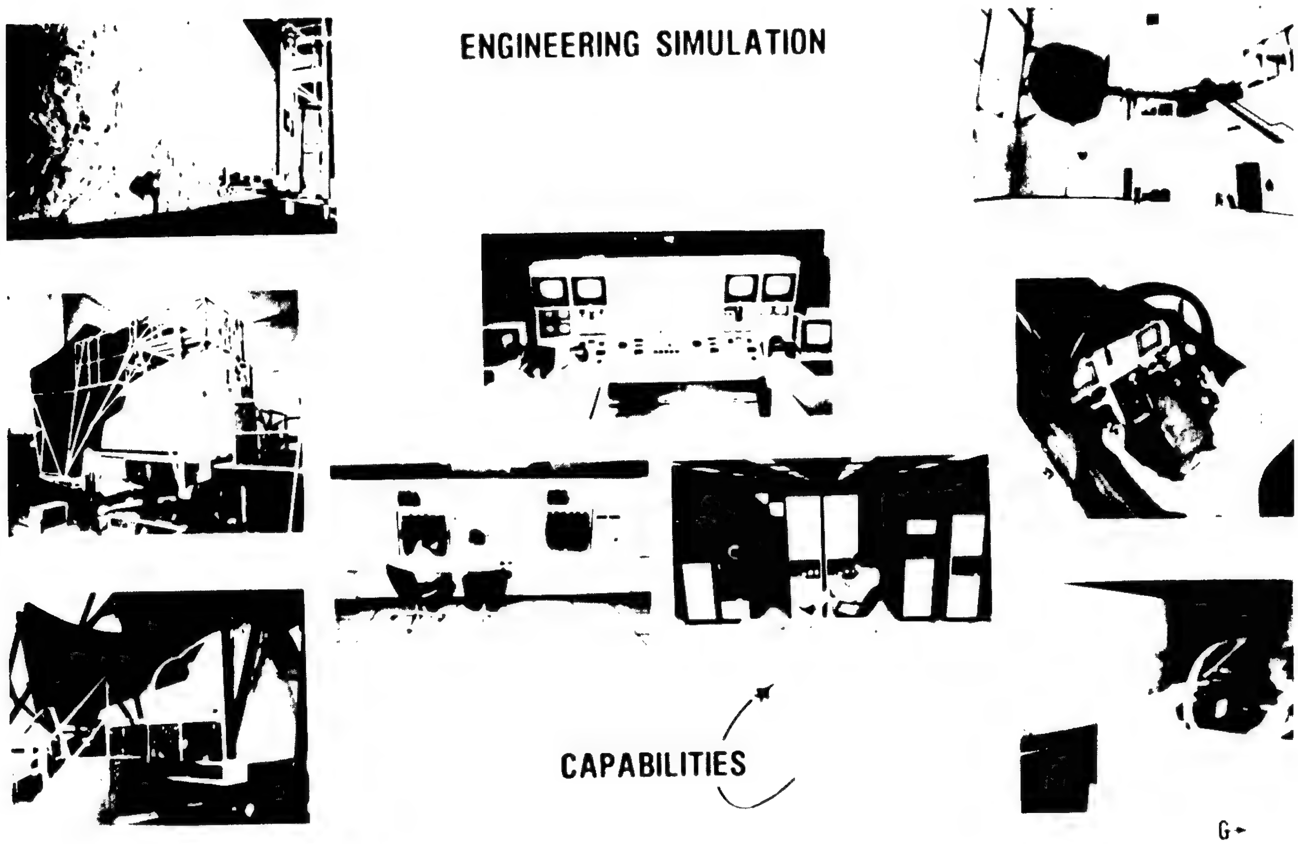
After 1964 the Control Equipment Branch, under Herb Basham, took over instrumentation research and development. At that time, illumination techniques, navigation and landing techniques, and cost and reliability were the major concerns. The new Branch also included human factors engineers and utilized the Flight Simulation Facility, which in the mid-sixties operated four simulators involving optimum integration of controls, displays and external vision. The facility's one fixed-base simulator was installed in Building 434 under a 24-foot planetarium dome showing 1500 stars which moved in response to controls synchronized with instrument displays. The facility's other three simulators were of the moving-base type. A standard T-37 cockpit was geared for approach and landing simulation under a wide variety of conditions. Another T-37 cockpit was modified to simulate a hypersonic flight vehicle capable of Mach 6, an altitude of 120,000 feet. It had speed



Medium STOL Transport cockpit simulator.



T-37 cockpit simulator in Building 633, used for approaches and landings.



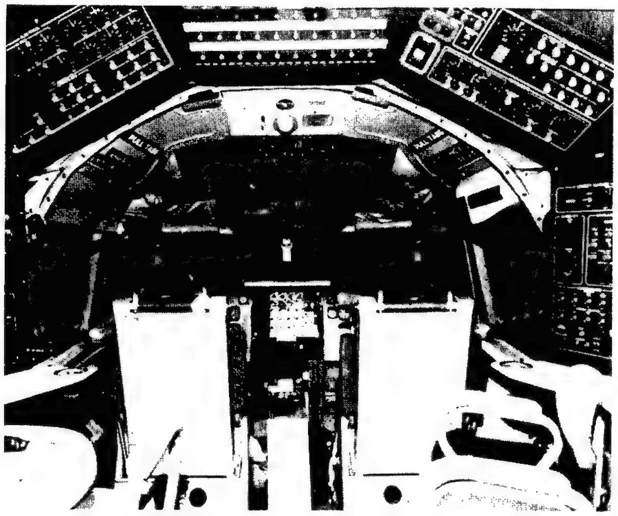
The Flight Control Division has always maintained several fixed and motion base simulators.

brakes, extensible wing tips, rocket boost, and other capabilities, and could be dropped from a mother ship. The third moving-base simulator was a Mark IV space capsule, a winged-body vehicle with five stages of mission: launch/boost, orbit, rendezvous, re-entry, terminal navigation and landing. It had a three-axis electrical control stick, advanced flight data displays, and a pictorial display on an approach-chart background. External controls were provided for engineers conducting the tests.

In the late sixties the Branch achieved great success in solid-state display technology, including high-contrast techniques, bulk-phenomena electronics and mechanization. Several new facilities were added, while others were phased out.

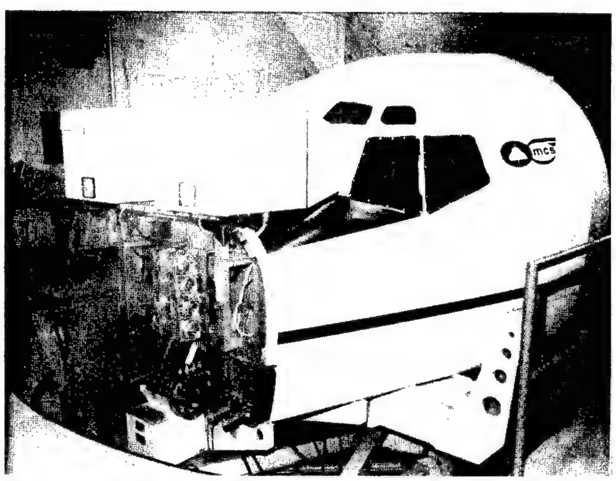
A "Motion System" was installed in the test facility to reproduce acceleration and direction of desired motion including pitch, roll and vertical translation. It consisted of three hydraulic cylinders controlled by four-way hydraulic servo valves. A photographic instrument synthesizer was built to simulate a proposed flight instrument on film. Using superimposition techniques, each moving part of the instrument could be added to the simulation, permitting detailed studies under dynamic conditions without actually building the proposed instrument. A digital flight simulation computer was purchased, and a helicopter simulator was modified to aid in the design of new instrument panels for V/STOL aircraft.

By the beginning of the seventies the branch had moved on to further studies of electroluminescent panels and was working on a primary controller to replace the control wheel in larger aircraft. The simulation group was studying high-contrast cathode ray tubes as replacements for electromechanical instruments, as well as on a vertical navigation situation display.



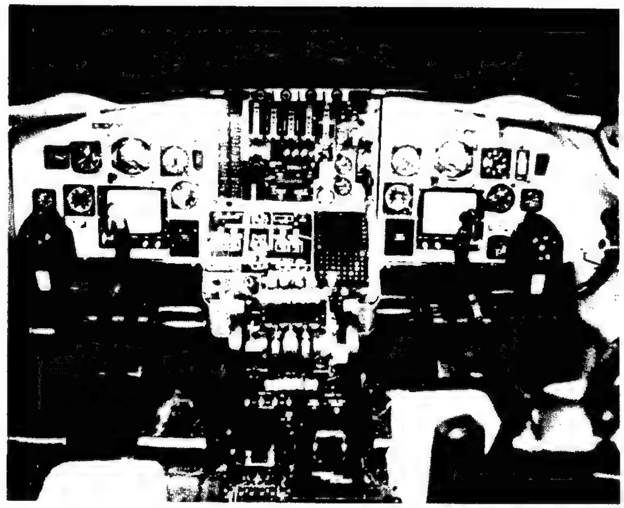
Cockpit simulators provide all the dials and gauges found in an actual aircraft, as in this KC-135 simulator.

Work had commenced on defining energy maneuverability display systems for high-performance aircraft, and on remote visual displays to augment panel displays during IFR-VFR (instrument flight rules to visual flight rules) transition. Control Systems Research Branch was providing support for a number of outside programs, including the Pilot Factors (PIFAX) project, TACLAND (Tactical Landing System), the Total In-Flight Simulator, and the VTOL (Vertical Take-Off and Landing) Integrated Flight Control System.



KC-135 tanker cockpit simulator, capable of providing the pilot with limited motion cues.

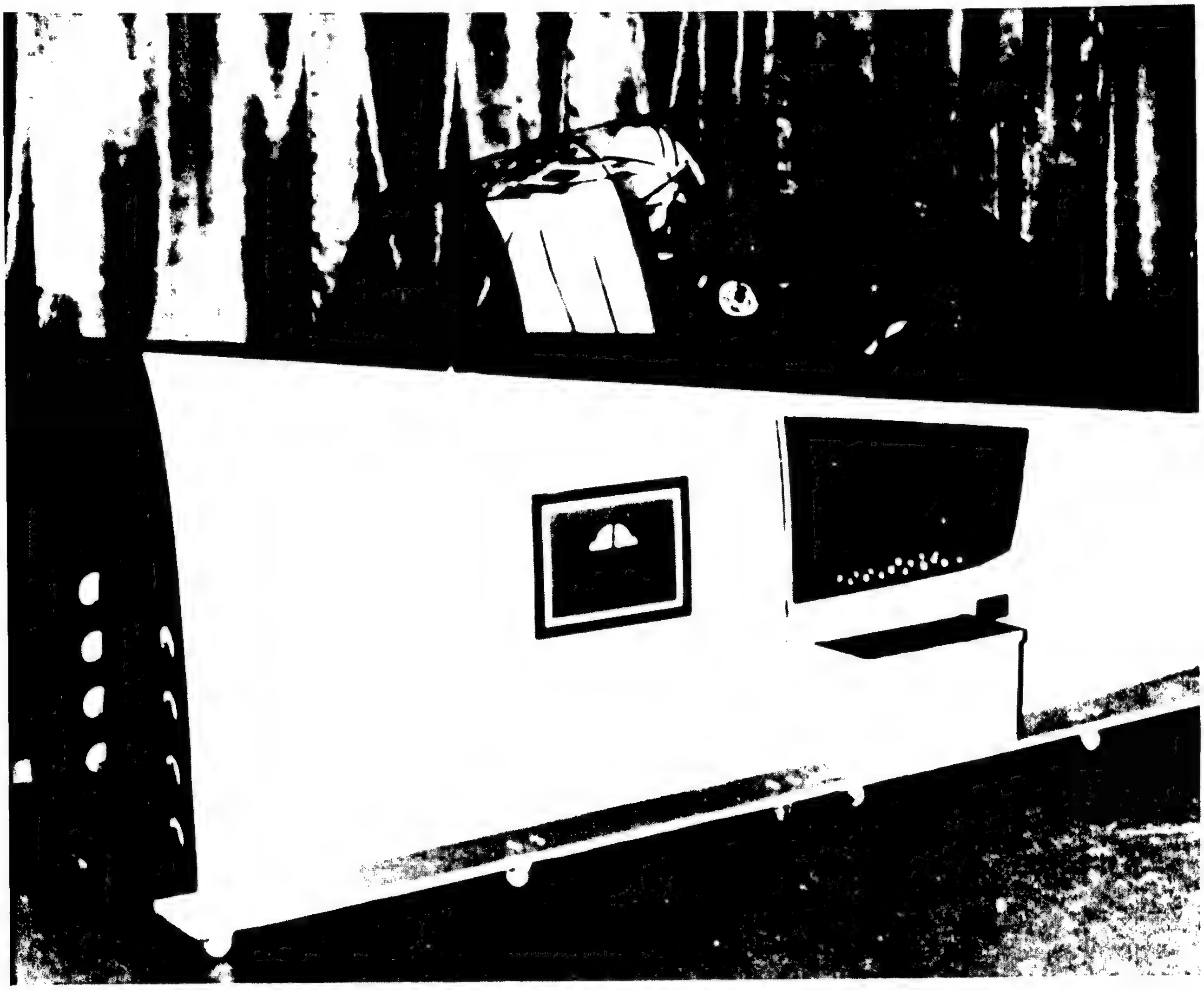
On the applied level, the branch built low-emission, high-contrast solid state displays for the KC-135 and the T-39. These were demonstrated under a wide range of visual-thermal ambient conditions, "a feat predicted impossible by some experts in the display field."



TRACE cockpit showing some of the complexities faced by the pilot of a four-engine transport. The CRTs help reduce workload.

The Flight Simulation Facility continued working with its modified helicopter simulator and the T-37 during the later seventies; work had begun on a modified C-135 cockpit to be mounted on a motion base and used with a Mark II digital computer. The new simulator broadened the Lab's understanding of V/STOL needs and on the concept of dividing pilot control duties among crew members.

In 1974 the reorganized Flight Deck Development Branch took over responsibility for instrument displays. The Advanced Control Display Group studied a variety of light-emitting and variable-reflecting materials, including gas discharge cells, liquid crystals, and lasers. With the discovery of light-emitting diodes (LED) new concepts in control display were rapidly developed. The instruments group concentrated on improving methods of displaying rate-of-closure information, building various

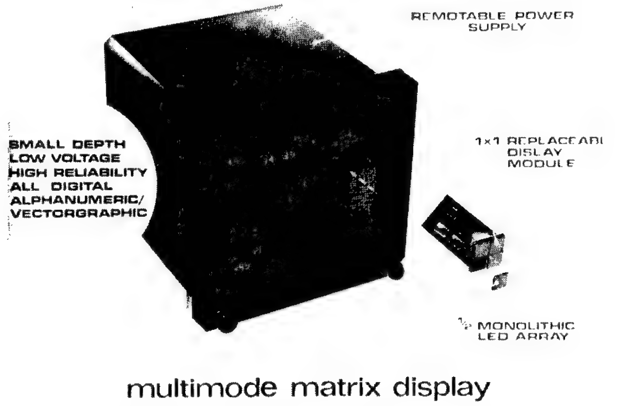


A pilot checks rearward visibility in this cockpit mock-up. All-around visibility is essential in combat situations.

head-up displays and designing helmet-mounted displays. The Crew Systems Integration group was at this time involved in a High Acceleration Cockpit Design Study and was developing new stores management techniques and improved displays for the one-man tactical fighter and the STOL transport. In addition, support was provided to the TACLAND, TIFS (Total In-Flight Simulator) and VTOL Integrated Flight Control System Programs.

Later in the seventies full-scale fighter mock-ups were in use for testing LED displays and cockpit lighting; a Digital Avionics Information System (DAIS) was under development to make better use of rapidly advancing computer technology.

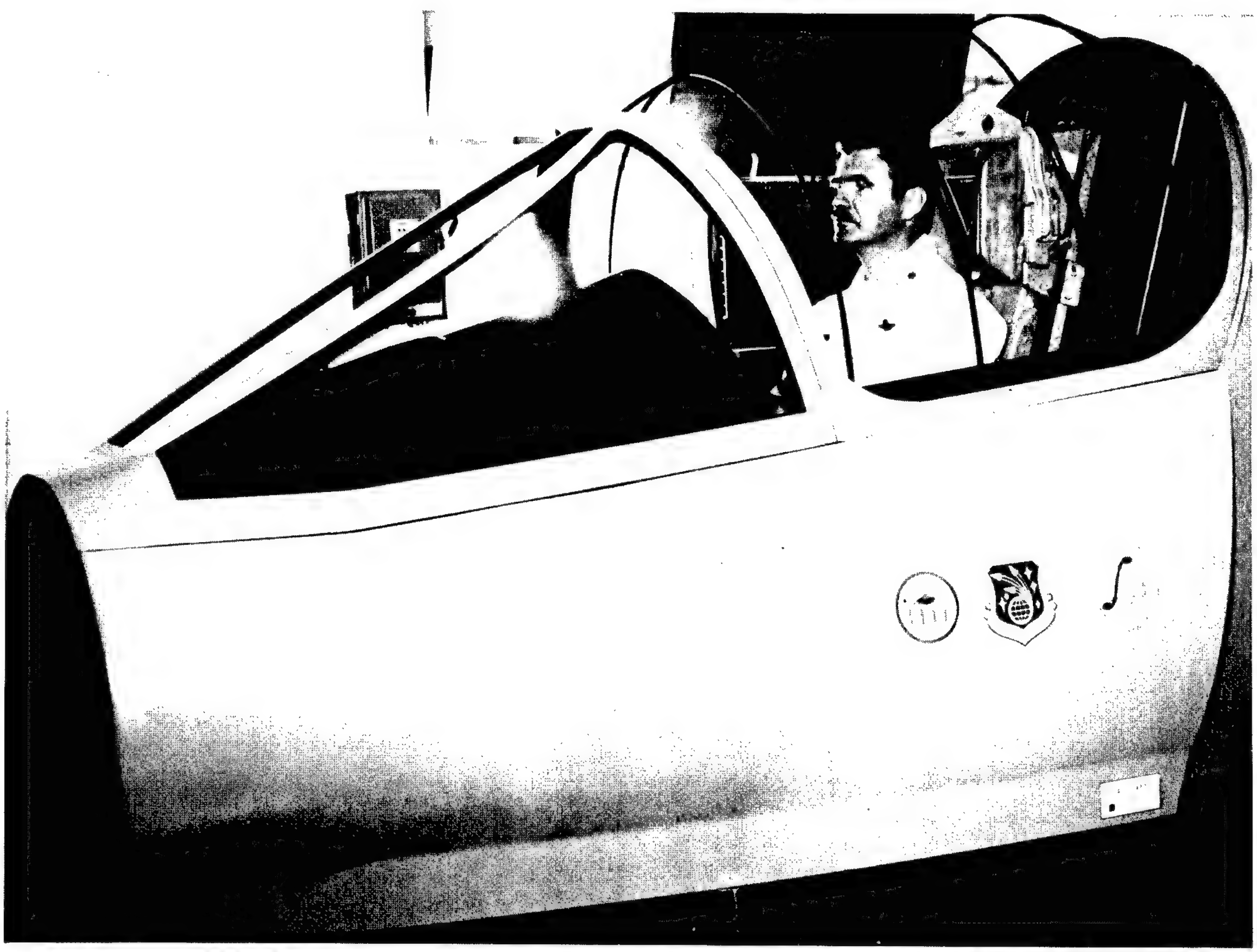
A human factors team joined the branch in the late seventies to study the interaction of pilots with the new digital displays. A C-130A crew workload study was under way to identify confusing procedures, peak area workload points and problems with control and display layouts. The Crew Systems Integration Group became the Control Display Branch in 1974, partly because of the extensive support it was by then offering to other projects outside the Lab. In addition to work already in progress, a Special Projects Group was set up to explore information



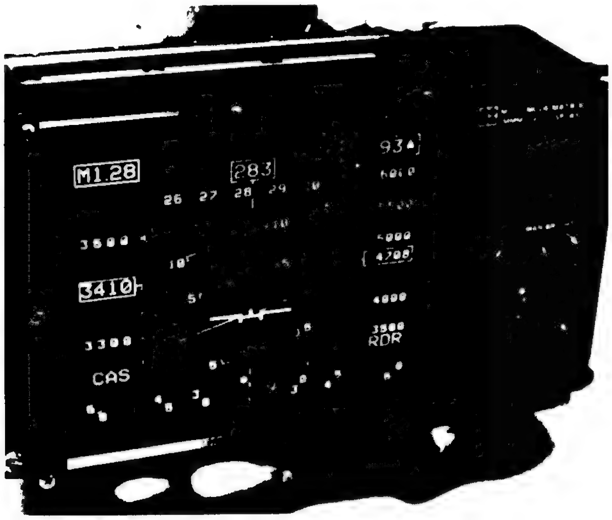
The Multi-Mode Matrix display provides more reliable and maintainable cockpit displays.

integration using multi-purpose display techniques. The DAIS project was continued, and the Multi-Mode Matrix (MMM) Display program was initiated. MMM uses flexible flat-panel, dot-matrix displays to facilitate information integration.

During the early 1960s, when many new weapon systems were still in the planning stage, it became evident that existing flight instruments and displays would be incapable of handling the flood of data provided by these systems. Electro-mechanical instruments would be too slow and too clumsy; more "agile" instruments would be needed. Pilots of the future would require vector-graphic/alphanumeric displays, moving pictorial maps, and other nontraditional

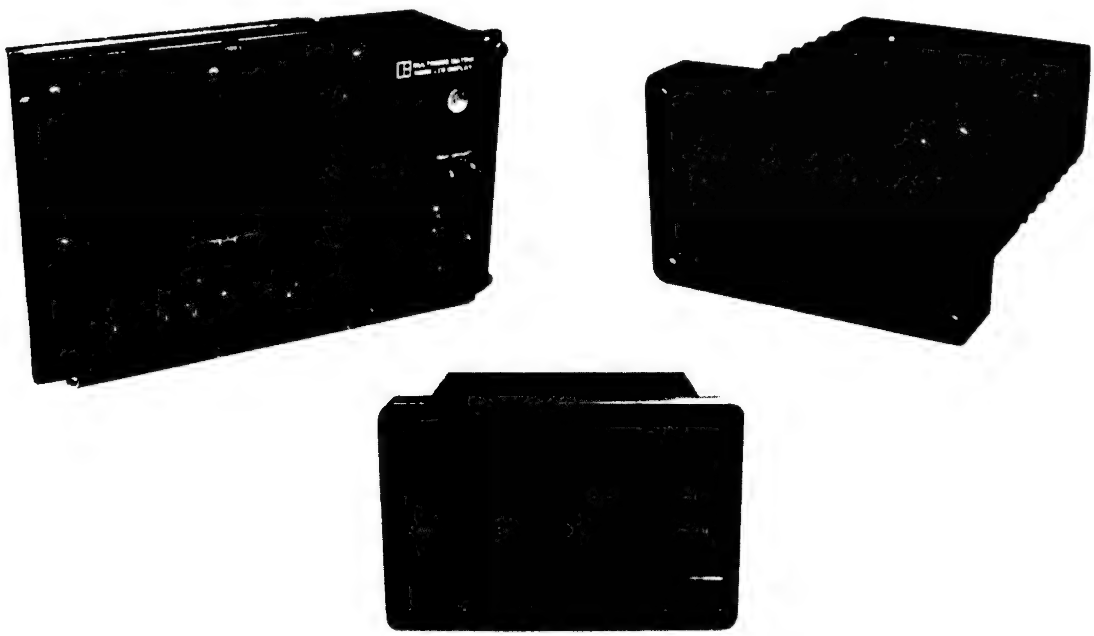


DAIS cockpit simulator used to investigate crew systems integration concepts.



Flat-panel Multi-Mode Matrix displays can be installed in shallower spaces than earlier CRT displays. They also weigh less and provide extra room for avionics or fuel.

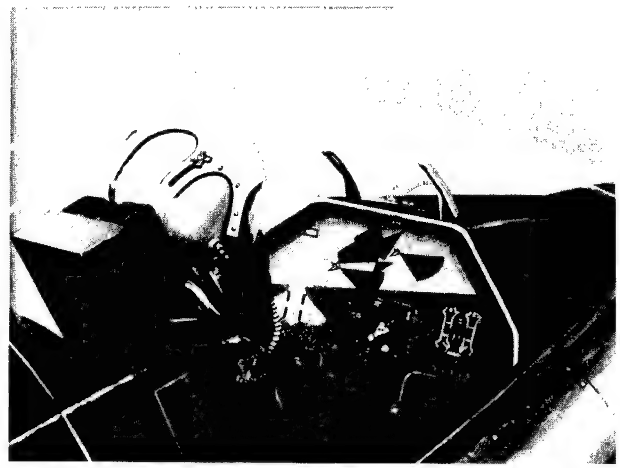
displays. Between 1972 and 1974 an FDL program demonstrated the feasibility of a vector-graphics display, provided that brighter LED arrays could be supplied. The Multi-Mode Matrix project was initiated to develop this technology. Its purpose was to show that large, practical area display faces could be constructed by abutting display modules without introducing visual discontinuities and electrical or optical coupling at the interfaces between modules. The color uniformity and light output of LEDs also had to be demonstrated. FDL contracted with the Canadian Department of Industry, Trade and Commerce (DOITC) to develop the necessary LED technology. Much of the work was done by Litton Industries under subcontract. After several delays caused by the experimental nature of the LED concept, an MMM display was delivered in December 1978, ready for flight testing. The feasibility of LED displays in a number of applications was also studied. Human factors research was conducted on dot-matrix displays in cockpit mock-ups and, later, in flight tests.



TYPICAL DISPLAY CONFIGURATIONS

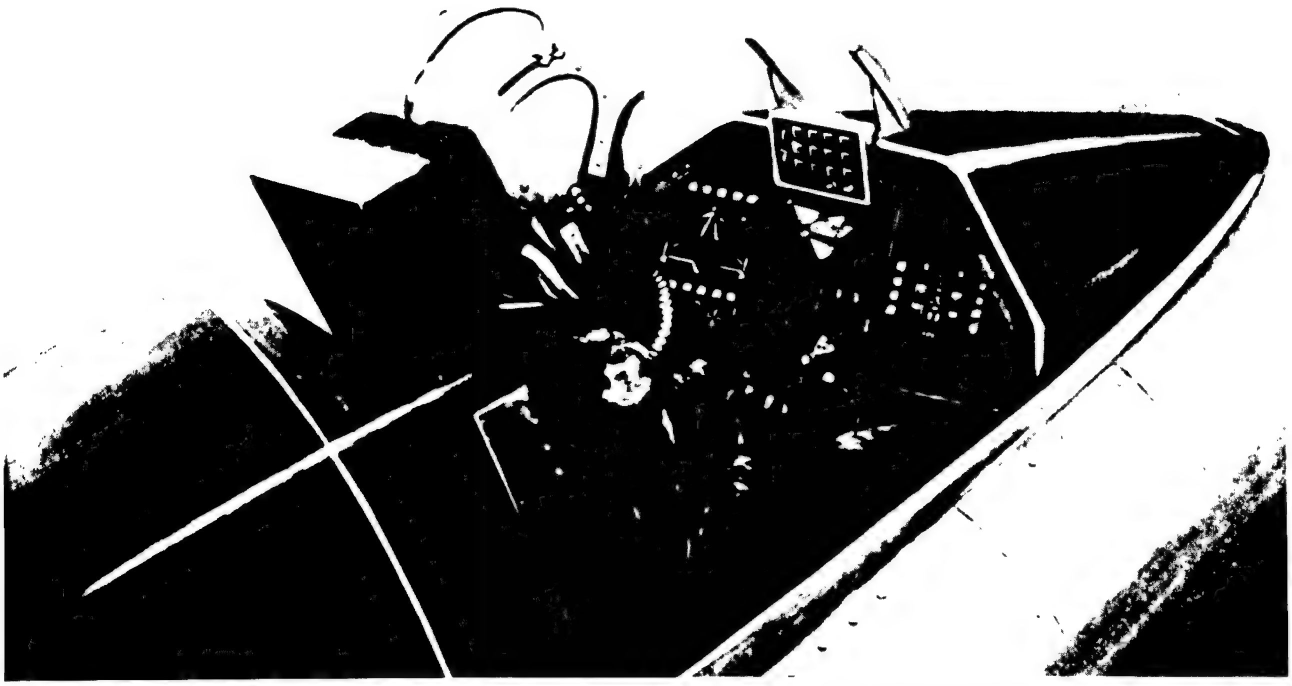
Future flat panel displays will use many colors and formats to aid the pilot in quicker comprehension of information.

Advances made in flight control data systems during the seventies greatly multiplied the amount of data available to the pilot, but existing instruments were incapable of presenting this information efficiently. This resulted in pilot information overload as well as increased workload, leading to diminished mission efficiency. In 1981 the Flight Control Division embarked on a project to create a Pictorial Display Format, replacing traditional electromechanical displays with computer-driven, TV-like displays. Full-color screens would permit presentation of color-coded information as well as pictorial displays. The Lab designed a number of different formats and the necessary software, and demonstrated that



Cockpit with elements of the fighter battle management concept on a panoramic display panel.

Advanced cockpit displays will increase the pilot's efficiency in future conflicts.



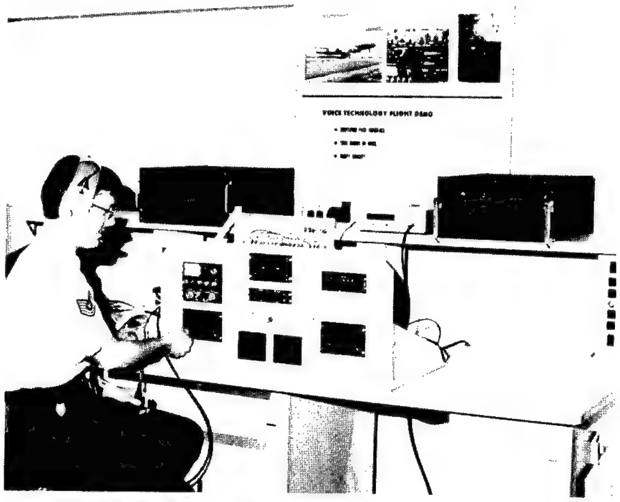
Pictorial format displays will probably replace most dials and gauges in future aircraft.

pictorial displays would be easier for pilots to learn and interpret.

Within two years the project began to pay off. Full-color pictorial displays were developed, showing flight data in a cartoon-like format integrating a large amount of data that could formerly be shown only as a series of numbers. Cockpit simulation was used, with primary flight, tactical situation, and systems status displays. Three side-by-side screens conveyed most of the information a fighter pilot needed to fly complex missions at low altitudes and in adverse weather conditions, at high speeds. It was becoming clear that the pilots of the future would primarily be involved in processing information and managing automatic systems, rather than in simply flying the airplane. Pictorial formats are ideally suited to this new requirement.

As fighter aircraft became more versatile, pilot workload quickly approached a saturation point. Pictorial displays are one means of dealing with this difficulty; voice control technology is another. During 1983 the Lab tested two voice-control systems in the AFTI/F-16 aircraft, demonstrating the feasibility of the technology. The effect of ambient noise on voice transmission and recognition was a stumbling block, but system accuracy during the tests exceeded 90%. Studies were conducted among pilots at Nellis

AFB and at the Aerospace Medical Research Laboratory, leading to the development of a data base capturing the degradation effects on speech due to noise, oxygen mask acoustics, and stress.



Voice control technology was tested at the Flight Control Division before it was used in actual flight.

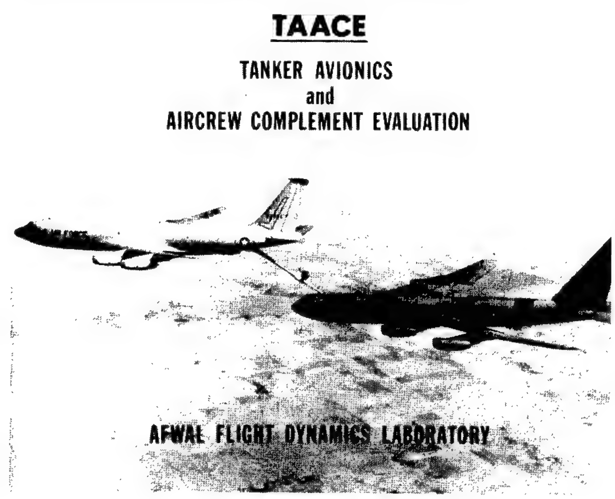
In 1984 a voice-controlled radio system was tested in a C-135C transport. This microprocessor-based system, with a 32-word vocabulary, permitted voice tuning of UHF and VHF radios. Over 100 hours of simulated flight showed a high rate of success. Voice-controlled radio systems are likely to be essential components of future aircraft designs, continuing the Lab's history of pioneering technological breakthroughs. Perfection of voice-control technology will mean a revolution in flight control. Heads-up operation and the elimination of most pilot hand motions will improve safety, reliability and reaction time.

Digital Flight Control

The Flight Control Division has developed a wide variety of applications for digital flight control technology, including a flight control system for the Navy's F-18. This fighter aircraft, though derived from the YF-17, has an entirely different flight control system, and utilizes advanced multimode displays.

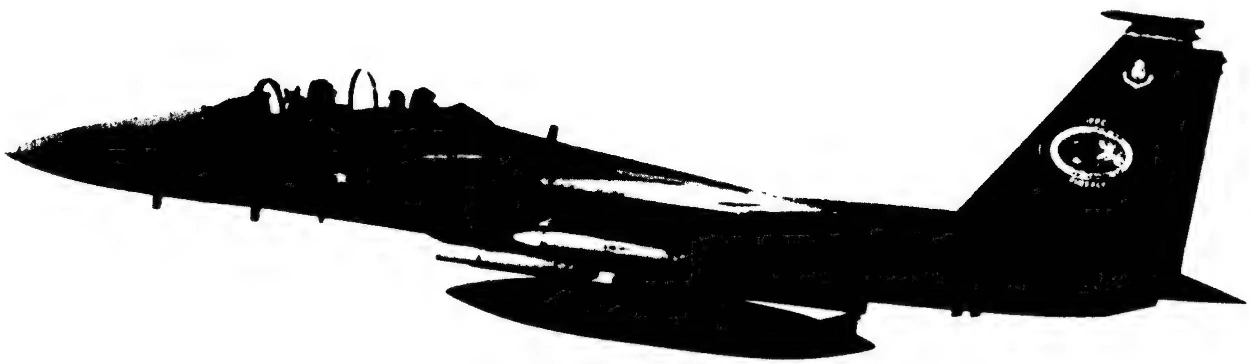
The related Digital Electronic Flight Control System (DEFCS), one of the major flight control successes of the past decade, consists of a dual channel configuration utilizing four Zilog Z-800Z microprocessors (two for pitch and two for yaw/roll) in a parallel processing architecture. The processor is capable of 495,000 operations per second and performs executive, control law computations, redundancy management, and built-in test functions.

The control system operates at 80 iterations per second. The software utilizes the Ada language (a standard Department of Defense computer language) with object code generated by a compiler optimized for time to meet the high system update performance requirements. The DEFCS is designed for coupling with other digital systems aboard the aircraft to provide integrated control capability. The system was first tested in an F-15 test bed and produced excellent results; it was an essential part of the Integrated Fire/Flight Control project.



TAACE helped prove that large aircraft missions can be completed without a navigator.

The Tanker Avionics and Aircrew Complement Evaluation (TAACE) program was completed in 1980 for the Aeronautical Systems Division. During this program SAC tanker crews validated a KC-135 cockpit designed to permit tanker operation without a navigator. A period of research and interviews with tanker crew



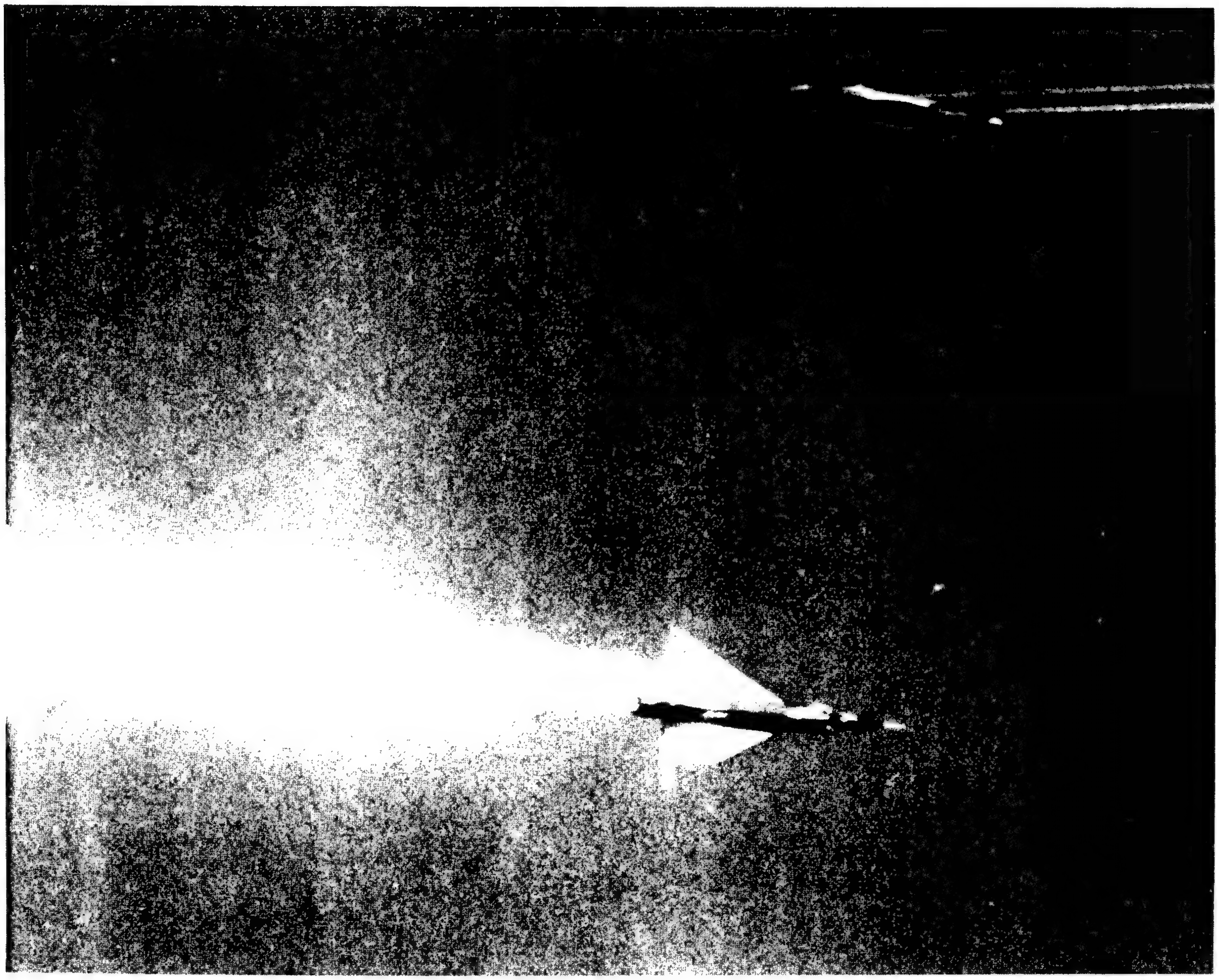
The F-15 IFFC program was a significant integration effort that tied the flight control system with weapon delivery software.

members was conducted, along with the development of three candidate mockups, which were then combined into a fourth composite configuration. Five SAC crews evaluated the new cockpit during full flight simulation of a variety of tasks, and all agreed that the configuration was workable without a navigator. The TAACE program set the standard for all subsequent crew station development.

IFFC

In 1980 the Flight Control Division embarked on one of its biggest projects to date: the Integrated Flight/Fire Control (IFFC) system. The purpose of IFFC was to improve weapons delivery accuracy and survivability in air-to-air and air-to-ground gunnery and bombing in fighter aircraft. The flight control, fire control and weapon systems were to be integrated, with the pilot as part of the control loop. The effort was co-sponsored with the Avionics Lab.

By 1981 an experimental IFFC system had been tested in a modified F-15. A digital computer coupler interface unit linking flight and fire control algorithms proved that the various components of an IFFC system could indeed be interlinked satisfactorily. A perfected system would soon enable fighter pilots to fire or drop



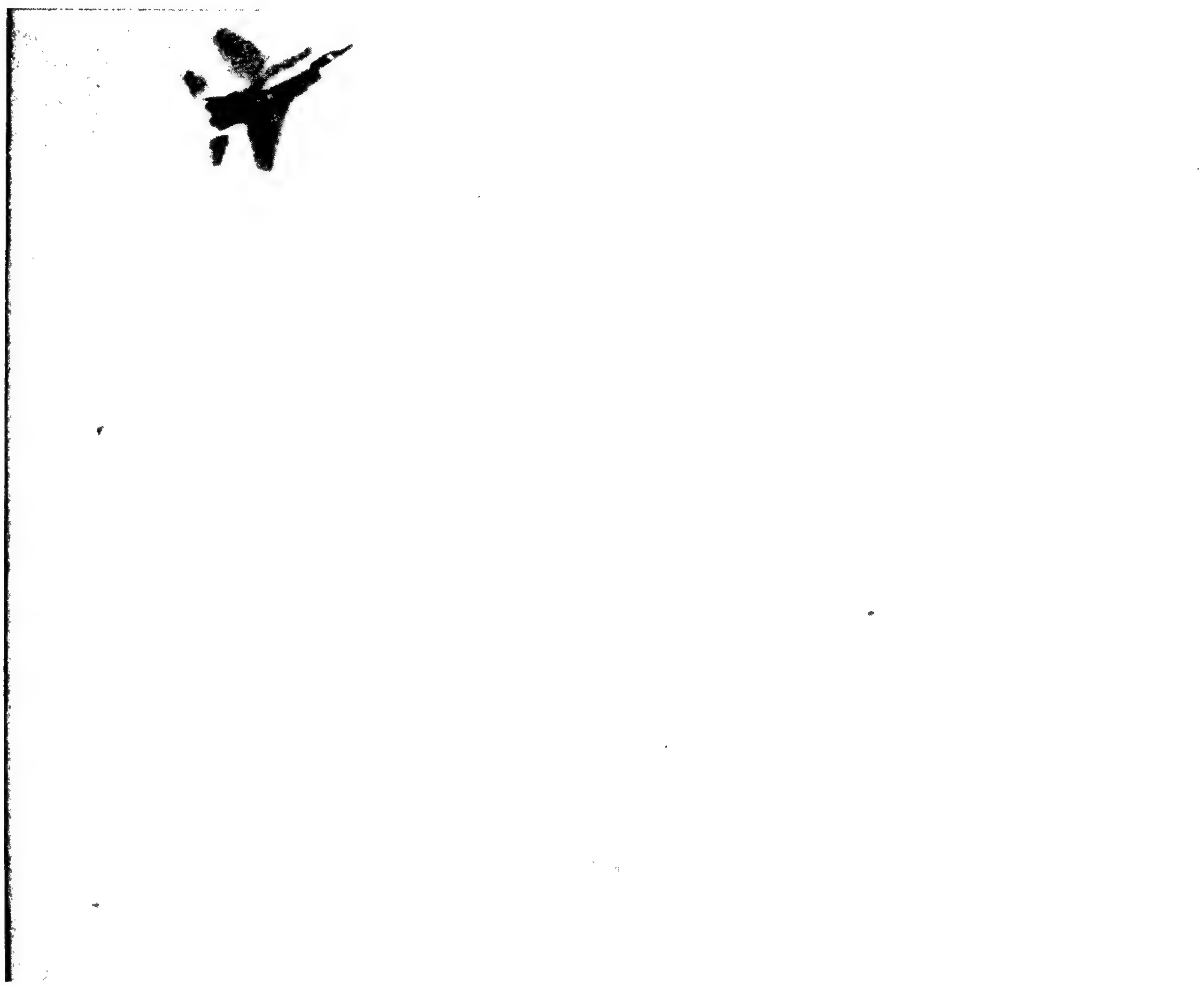
The F-15 IFFC "Firefly III" overflies a remotely piloted target aircraft which it has just shot down.

weapons accurately while flying attack profiles that had been considered impossible.

During 1981 and early 1982 thirteen "Firefly III" missions were successfully flown, delivering 20mm bullets and practice bombs during 3.5G approaches and at ranges up to 17,000 feet. Dusk Tracer and Target State Estimator missions were flown to augment the air-to-air gun mode, and an Onboard Simulation device performed satisfactorily. Weapons delivery accuracy was increased while pilot workload was reduced. Improved survivability against antiaircraft defenses was also demonstrated.

In a mock air-to-air engagement in 1981 against a remotely piloted PQM-102 aircraft, the F-15B destroyed the target with a single burst from its 20mm Vulcan cannon in a dynamic high angle of attack and high closing speed on its first pass. The PQM-102 was approached from the front quarter at a velocity of more than 880 miles per hour. The pilot was recorded as saying, "I don't know if I got it or the computer got it, but we got it!" The F-15B also demonstrated the capability to deliver bombs under previously unfeasible flight conditions such as curved flight paths, and the results suggest a tenfold increase in survivability.

The number of successful IFFC missions reached one hundred and six by the end of fiscal year 1983, and this outstanding success rate



The true significance of integrated flight and fire control system: increased kill capability.

stands as one of the Flight Control Divisions's most impressive accomplishments. These results demonstrated that the weapon delivery trajectory must be generated by the integrated flight/fire control system rather than in the avionics system.

Control Analysis and Optimization

Though the Engineering Lab enjoyed outstanding success in the design of new control systems in the early 1950s, its engineers recognized that even "the best" can always be improved. No single control concept is best for all aircraft; vehicles and their missions differ widely, and each requires fully integrated controls for optimum performance. Beginning in 1954 the Lab, as a result of the reorganization, launched a systems analysis program to provide guidelines for future control systems designers. Wright Air Development Center began by gathering the largest collection of data on performance failures ever assembled, and then analyzed these data in order to create general theories of flight control reliability and "standard operating procedures." This program also produced cost and development time guidelines which were used extensively by the armed forces, private industry and NASA.

The Flight Control Division has always had a systems integration branch under one name or another, and the other branches have usually had

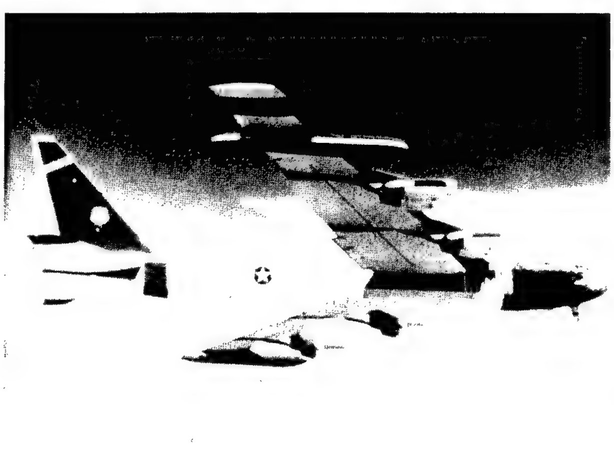
their own analysis and integration groups. The Systems Integration and Flight Experimentation Branch, in the early 1960s, was responsible for integrating the output of the other branches, conducting demonstrations, and providing support for advanced weapon systems analyses. Among its early projects were Program 667A, Integrated Flight Control for Advanced Aerospace Vehicles; the Pilot Control/Display-Factors Program for the Supersonic Transport, and "Micro-Vision," a low visibility monitor display landing aid. In 1966 this branch, in support of the V/STOL Division, assumed responsibility for the VTOL integrated flight control system and evaluated a TALAR transmitter for use as a ground guidance device for approach and landing in remote areas. Studies were conducted on a new control wheel with function selector switches installed on the wheel for easier access.

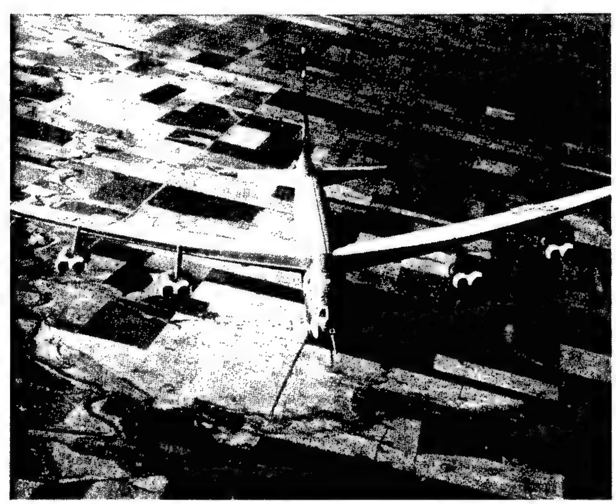
In the 1970s a major project was the Microwave Landing System (MLS), part of a national program to upgrade the all-weather landing capabilities of military and civilian aircraft. MLS was adopted as the global standard at an International Civil Aviation Organization Conference in April 1978. The Flight Control Division provided the technical lead that made this decision possible.

By 1968 support for the VTOL effort had grown, and the branch had also commenced a Loads Alleviation and Mode Stabilization Program (LAMS) aimed at extending structural lifespan. Tests were being conducted with a modified B-52 at Boeing Wichita.

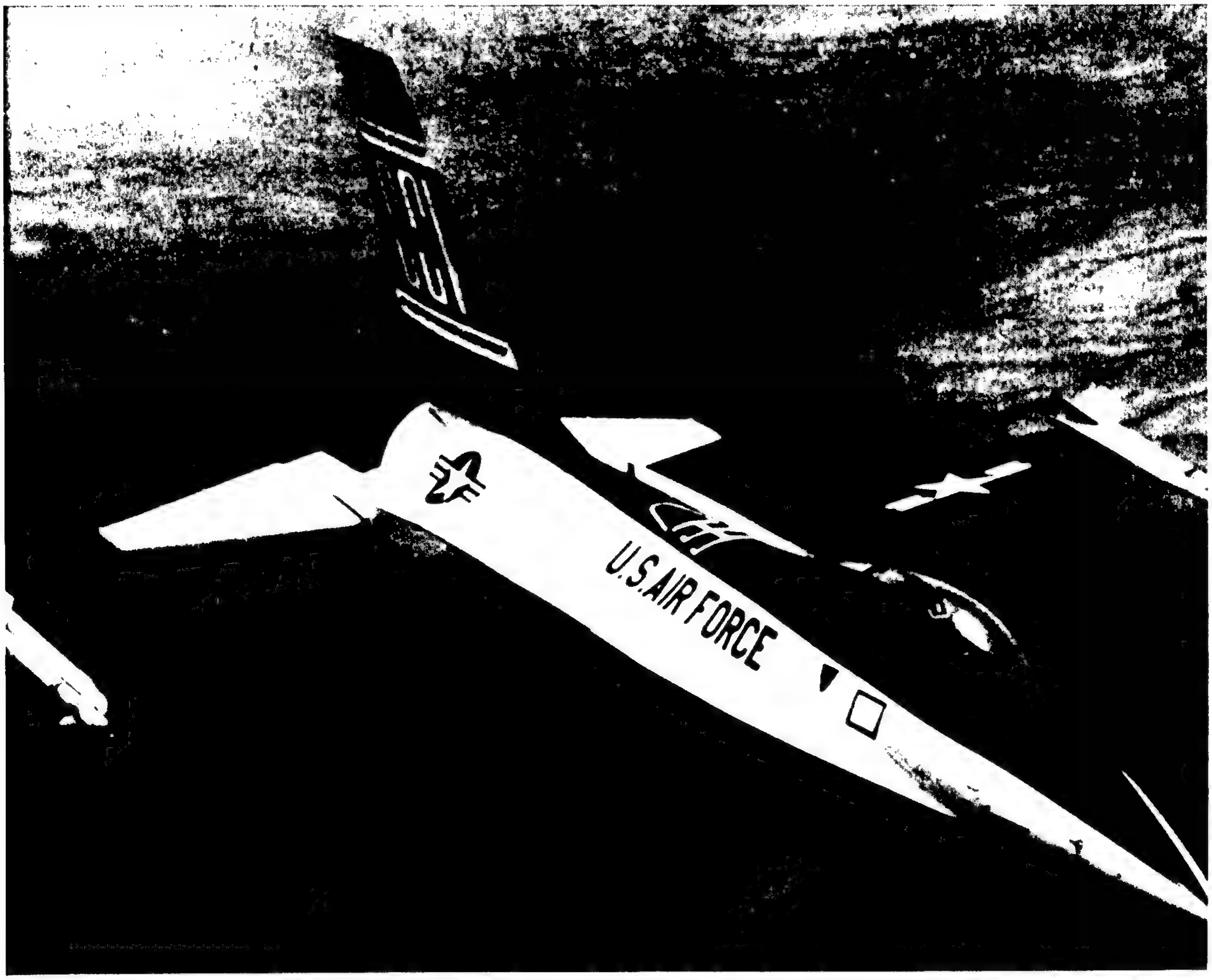
The Tactical Landing System (TACLAND) program (1968-1971), an effort to improve flight control under adverse weather conditions, eventually grew into the independent Terminal Area Control Branch, which began operations in 1976. Existing air traffic control technology was rapidly becoming outdated, as larger numbers of dissimilar aircraft had to be controlled over larger areas. The Flight Dynamics Lab, working with the FAA, now took on a large part of the responsibility for a planned worldwide data link communication and navigation system. The Branch began exploration of the possibilities inherent in digital computers, and of synthetic visibility techniques. This technology has been widely applied in air traffic control systems, while progress continues on the global data link concept.

A Flight Experimentation Group was established to conduct tests in the Pilot Factors (PIFAX) and similar programs. Later, the Engineering Flight Simulation Group took over management of the Lab's simulation facilities.





The B-52 LAMS program utilized extra flight control surfaces near the aircraft nose to help reduce flight loads.



The F-16 CCV program used canards located near the inlet and an advanced flight control system.

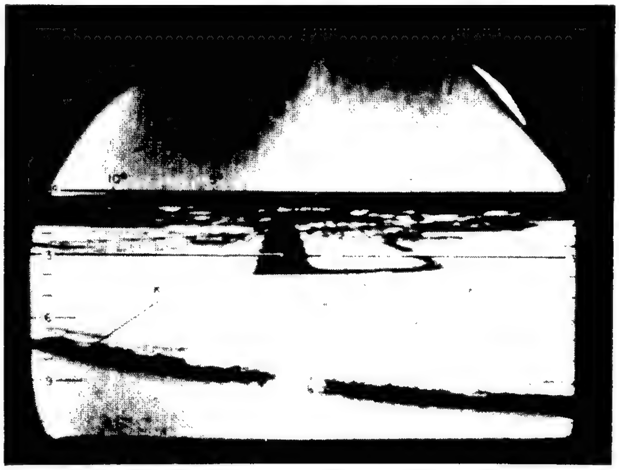
In the early seventies the new Systems Dynamics Branch assumed responsibility for all simulation equipment. The Engineering Flight Simulation Group soon developed the capability to simulate the full mission profile of nearly every existing and projected weapon system. Its efforts then included the control-configured vehicle aspects of the F-16, and development of controls for the STOL transport.

The Systems Analysis Group evaluated the preliminary studies of the IFFC (Integrated Flight/Fire Control) project, helped develop a control system for the High Altitude Supersonic Target Missile, and assembled a library of computer programs.

All-Weather Flying

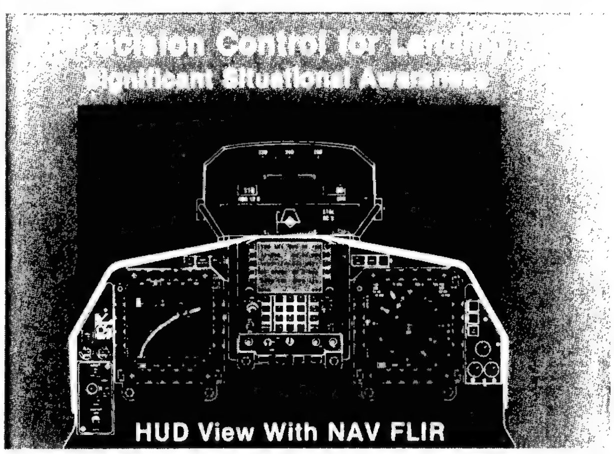
The ability of aircraft to fly in adverse weather conditions is taken for granted today; but in fact, the all-weather flying systems used in most civilian and military aircraft owe their existence to the Flight Dynamics Lab. Work in this field began at the old Airplane Lab more than half a century ago, and made considerable strides during World War II. However, during the 1980s the work of the All-Weather Experimentation Group (originally within the Flight Research and Test Branch) has assumed increasing importance. One of its early projects was the Independent Landing Monitor (ILM), designed to enable

aircraft "to fly precise curved and segmented paths with time constraints for both departure and arrival routes." The ILM system can greatly reduce delays and save fuel, in military as well as commercial aircraft.



Symbols superimposed on the image provided by the Independent Landing Monitor.

This group also explored an autonomous landing guidance concept, applicable to tactical aircraft required to land at night or in poor weather at unprepared, battle-front airfields. An autonomous landing system would enable a pilot to determine, without help from the ground, whether a landing under such conditions was feasible and safe. Multiple sensors operating across a wide spectrum of frequencies provide a synthetic visual image of ground conditions. This idea was under active development in 1988 by a joint AF/FAA program. Radar is used to produce an image on a heads-up display; flight path commands are generated by the control computer from the sensed data for the inertial navigation system.



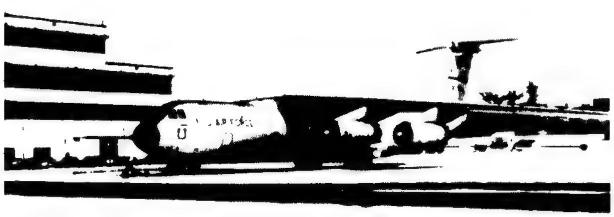
This cockpit display panel looks complex, but its autonomous landing guidance system actually makes the aircraft easier to land.

In addition, this branch conducted tests with a modified CH-3E helicopter demonstrator, to explore means of mixing automatic flight control systems with pilot stick motion. This technique eliminates feedback through a series-parallel servo system and filtering network.

CH-3C helicopter demonstrated an automatic flight control system tied to pilot inputs.

In the mid-seventies the All-Weather group concentrated on a joint Federal Aviation Administration/USAF program to develop low visibility landing technology for cargo and bomber type aircraft. Testing was conducted on the psychological, physiological and procedural difficulties of the concept, and a study of the pilot's control/display and external vision requirements was completed. The group considered the feasibility of a combined Electronic Attitude Director Indicator/Approach and Landing Radar, and evaluated the Category III Instrument Landing System (ILS) ground system. Once a technical base was established a C-141 was modified for flight testing, with a

four-dimensional navigation system and associated command augmentation systems. Trade-off and redundancy requirements were established and various capabilities of both pilot and system were determined, allowing the Lab to set new human factors standards for maximum cockpit utilization of information. The Lab's C-141 was then the only aircraft authorized by the FAA to fly Category III 0-0 weather landing conditions.



This C-141, used to test landing guidance and control systems, is the only aircraft certified to land in zero visibility weather.

Advanced Development

During the 1970s the Flight Control Division conducted a number of advanced development programs. For example, the Control Configured Vehicles (CCV) project led to a significant weight reduction of ride, maneuver load, and flutter controls, and generally improved the maneuverability and mission effectiveness of tactical fighter aircraft through improved controls. Flight testing was conducted under contract with McDonnell Douglas in a modified F-4E, then with an NB-52E formerly used by the LAMS program, and most important, with the F-16.

The Advanced Fighter Cockpit Development Program, a major accomplishment of the early 1980s, studied ways of using state-of-the-art display technology to integrate and present all the information needed by the fighter pilot. The Digital Synthesis Simulator (DIGISYN) and the F-16 Cockpit Dynamic Mock-up at the Flight Control Division were used for this project. Experienced pilots "flew" difficult missions while performing a variety of complex tasks, helping to identify the optimum cockpit instruments and displays. This program will help reduce pilot workload in the advanced fighters of the 1990s.

A major new program that will get under way in 1989 is the Variable Stability In-Flight Simulator Test Aircraft (VISTA), a modified F-16D. The aircraft is an Israeli version of the F-16 which already has the extra fuselage space needed for the variable stability computer and other equipment. VISTA will be capable of simulating the flight characteristics of a variety of aircraft, from an Advanced Tactical Fighter to the National Aerospace Plane. Its flight controls will be adaptable enough to simulate the cockpit of many current and planned aircraft, and different computer programs will be used to make the F-16D handle and react like those vehicles. To be built by General Dynamics, the VISTA will probably begin flying in 1992, and will replace the Division's NT-33 simulator which has been in use since 1957.

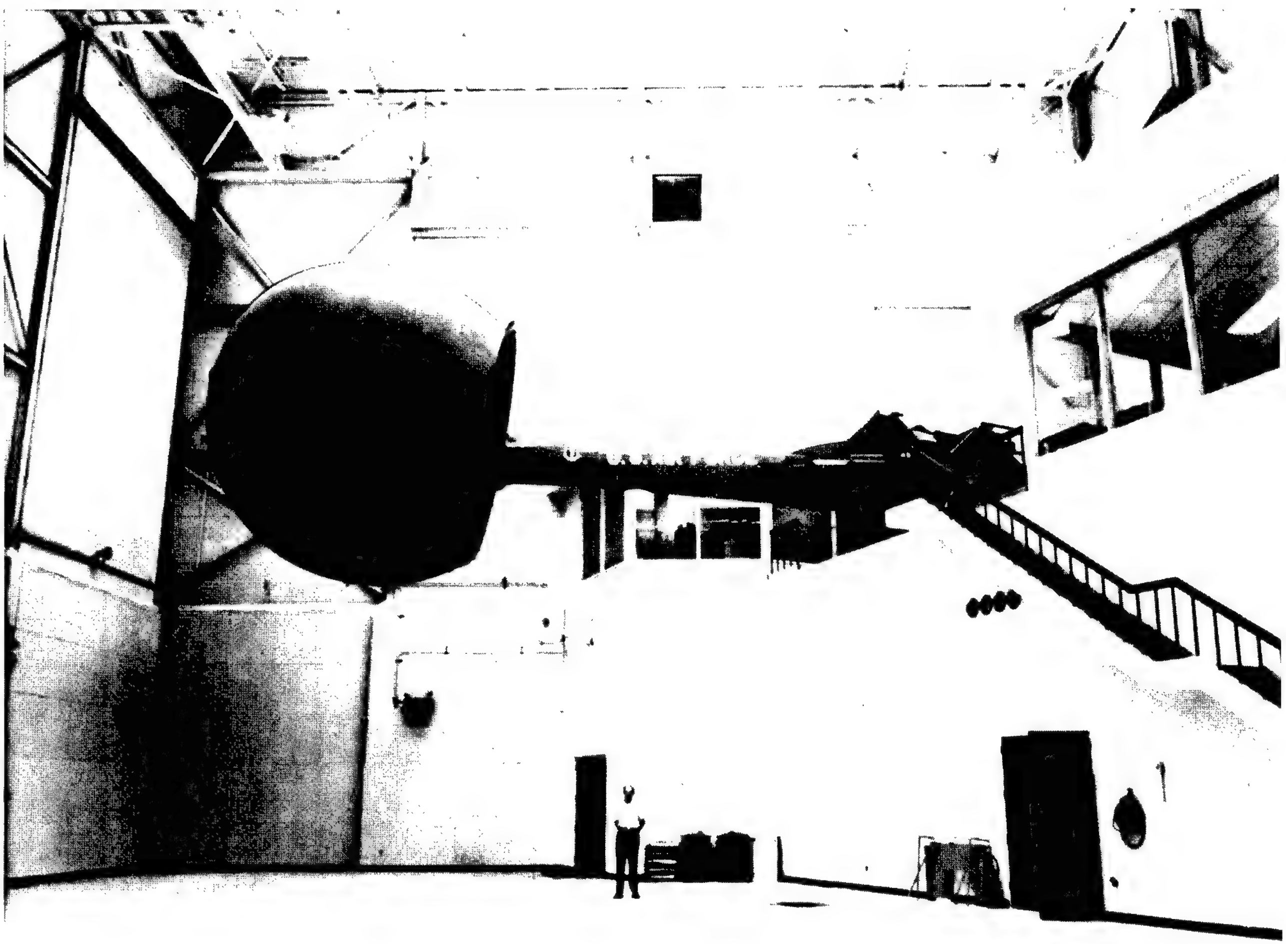
Moving into the next decade, the Flight Control Division expects to contribute some two dozen new or improved technologies under Project FORECAST II. Areas include integration of control and avionics systems for tactical air superiority; hypervelocity control and crew systems technologies, and improved all-weather landing for fighter aircraft. Techniques for designing control systems with highly integrated and interactive elements for aerospace applications will be developed, along with fault-tolerant control systems to provide uninterrupted and safe operation under battle conditions or internal failures. Crew/vehicle integration work will continue, with a goal of applying artificial intelligence technology to

reduce crew workload and achieve capability for single-seat, night, all-weather ground attack. Expansion of the technology core is a major goal for the 1990s, in such areas as supermaneuverability, agility, STOL fighters, and reconfigurable flight control. The MAGIC facility and other in-flight simulators will play an essential part in this work.

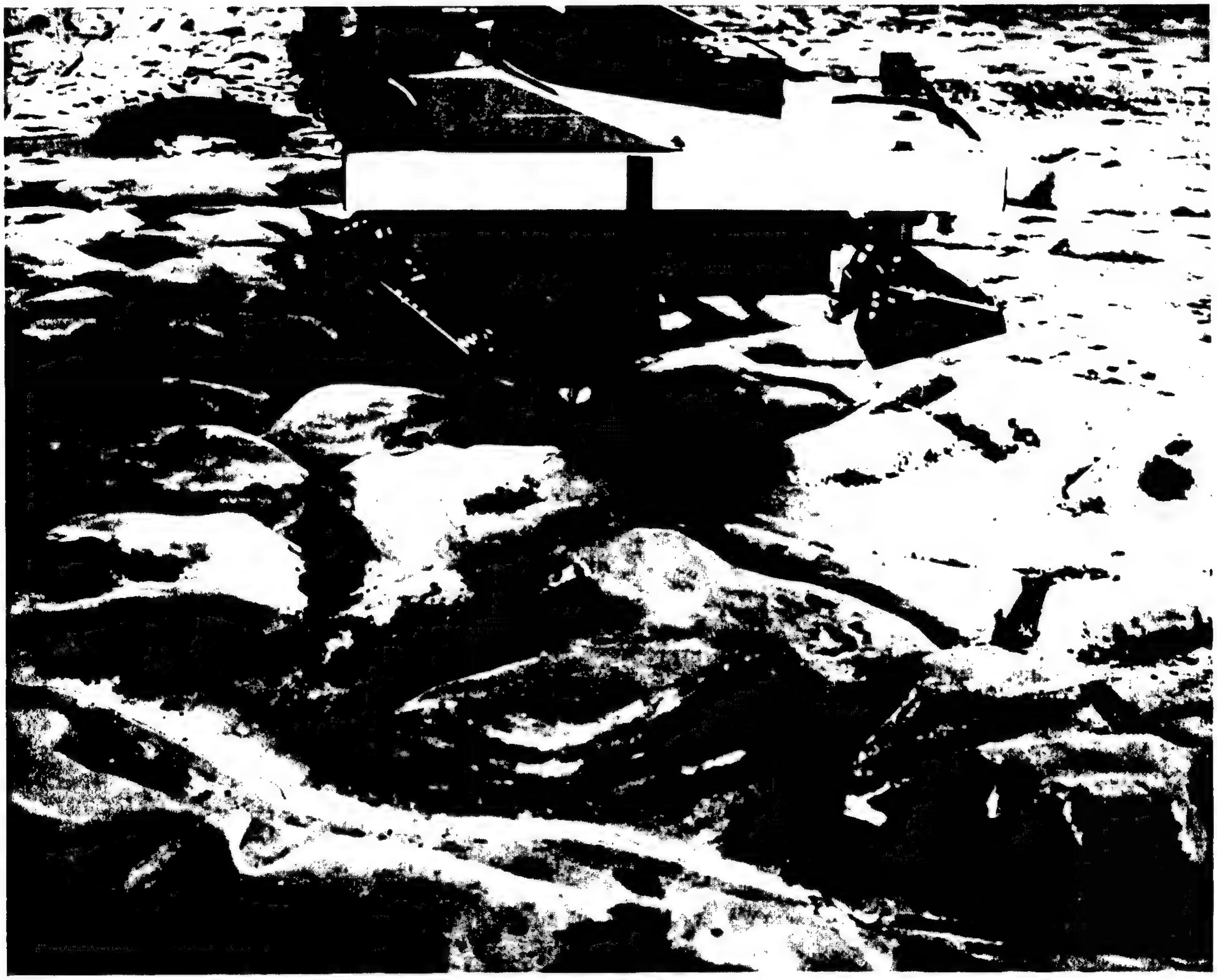
Of the various divisions of the Flight Dynamics Lab, Flight Control has always worked most closely with the Avionics Lab, and this partnership is expected to become more critical in the coming decade. Miniaturization and cost reductions in digital technology have made possible a greater integration of flight control and avionics systems. For example, the fire control sensors and the flight control system can be designed to converge on the weapon delivery system. Integration does not solve every problem, however; the differing requirements of avionic and control systems prevent channeling all information through a common data bus. In the future, research will emphasize applications for artificial intelligence technology.

Current Facilities

The West Wing (Building 145) now contains four flight simulators. The Large Amplitude



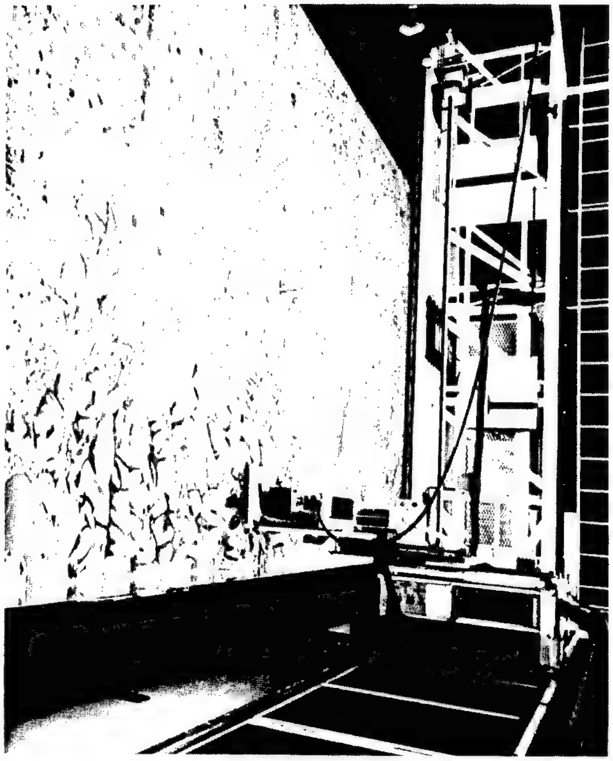
The LAMARS motion flight simulator can give the pilot cues in five of the six degrees of freedom experienced during actual flight.



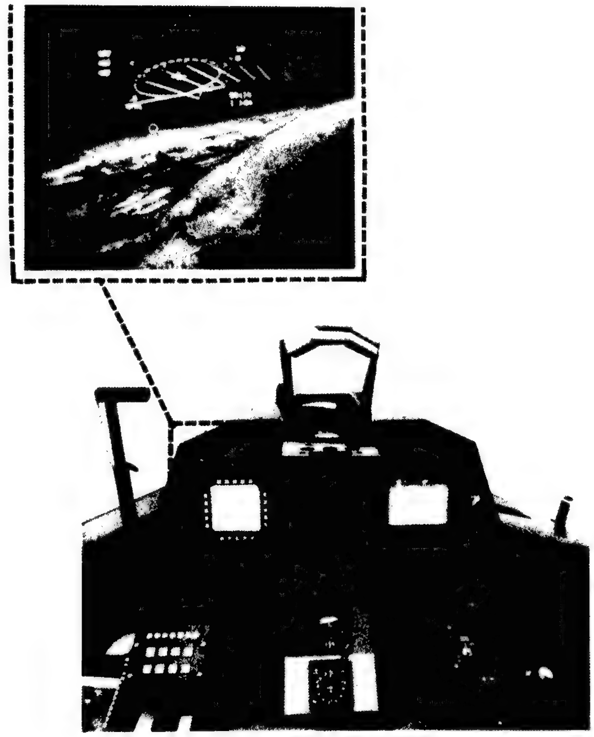
A video camera projects a display on the dome above the LAMARS cockpit.

Multimode Aerospace Research Simulator (LAMARS) consists of a five-degree-of-freedom beam-type motion system with a single-space cockpit on the end of a thirty-foot beam. The on-board visual display system utilizes a spherical projection screen with a radius of ten feet and a 266-degree field of view. The cockpit can be rigged to simulate all modern fighter aircraft. Recently this facility was used to simulate the F-16 LANTIRN (low altitude navigational targeting instrument rating for night) aircraft to study implementation of automatic terrain following algorithms in a realistic threat and rough terrain environment. There are also two motion-base simulators: one capable of pitch, roll and heave, and a fighter/bomber simulator configured for low-altitude penetration and weapon delivery scenarios. All three simulators utilize the Rigid Model Visual System, containing two illuminated three-dimensional terrain models with gantry-mounted television cameras. Data for all simulators are collected by the Hybrid Computer Complex. Pilot-instrument interaction is studied in the Tactical Aircraft Cockpit Study (TACS) simulator.

The East Wing (Building 146) provides 84,900 square feet of laboratory space. There are crew

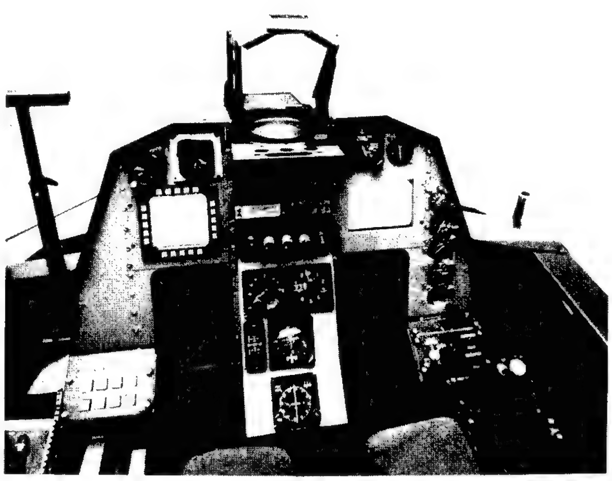


The LAMARS camera actually flies over this three-dimensional terrain board, corresponding to the pilot's controls in the cockpit simulator.



The Terrain Following/Terrain Avoidance concept was "flown" by the LAMARS 3-D terrain board.

station simulation rooms, a machine shop, photographic facilities, and labs for all aspects of flight control development.

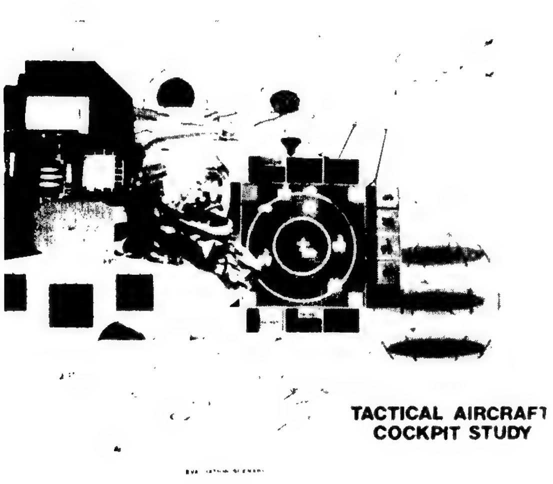


The LAMARS can be adapted to simulate many different fighter cockpits. Here it is set up to represent the AFTI/F-16 cockpit.

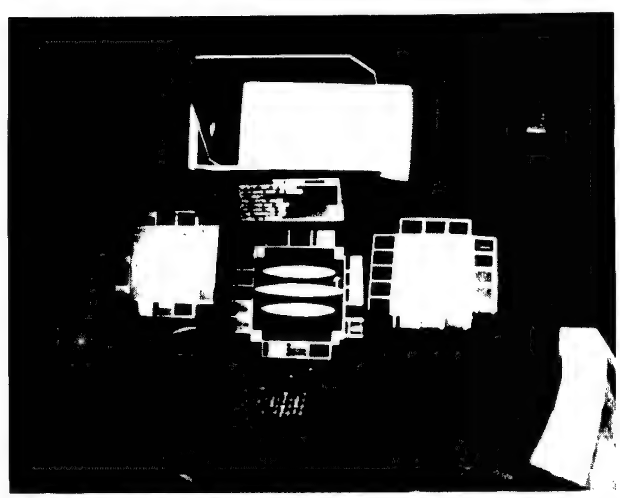
The MAGIC cockpit (Microprocessor Application of Graphics with Interactive Communications) is a low-cost research tool developed to evaluate design concepts at relatively low fidelity levels before a decision is made to allocate funds to more expensive simulator investigations. MAGIC includes pictorial displays, color and multifunctional displays, touch sensitive overlays, programmable switches, and voice control systems. The Tactical Aircraft Cockpit Study (TACS) facility is also located in this building. TACS is a dynamic cockpit with computer support, designed to investigate advanced control and display technologies in a system context.

In addition, the Flight Control Division operates the "Speckled Trout" flight test aircraft, a modified C-135C which has been used to test such technologies as the Dynamic System Identification and Modeling (DYSIM) program. DYSIM involved the in-flight refueling of a

The MAGIC cockpit conducts research on pictorial formats, design concepts and configuration arrangements.

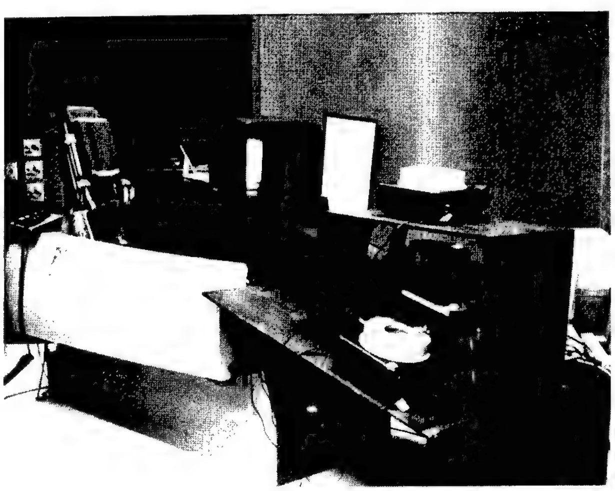


Flight Control Division's TACS simulator.



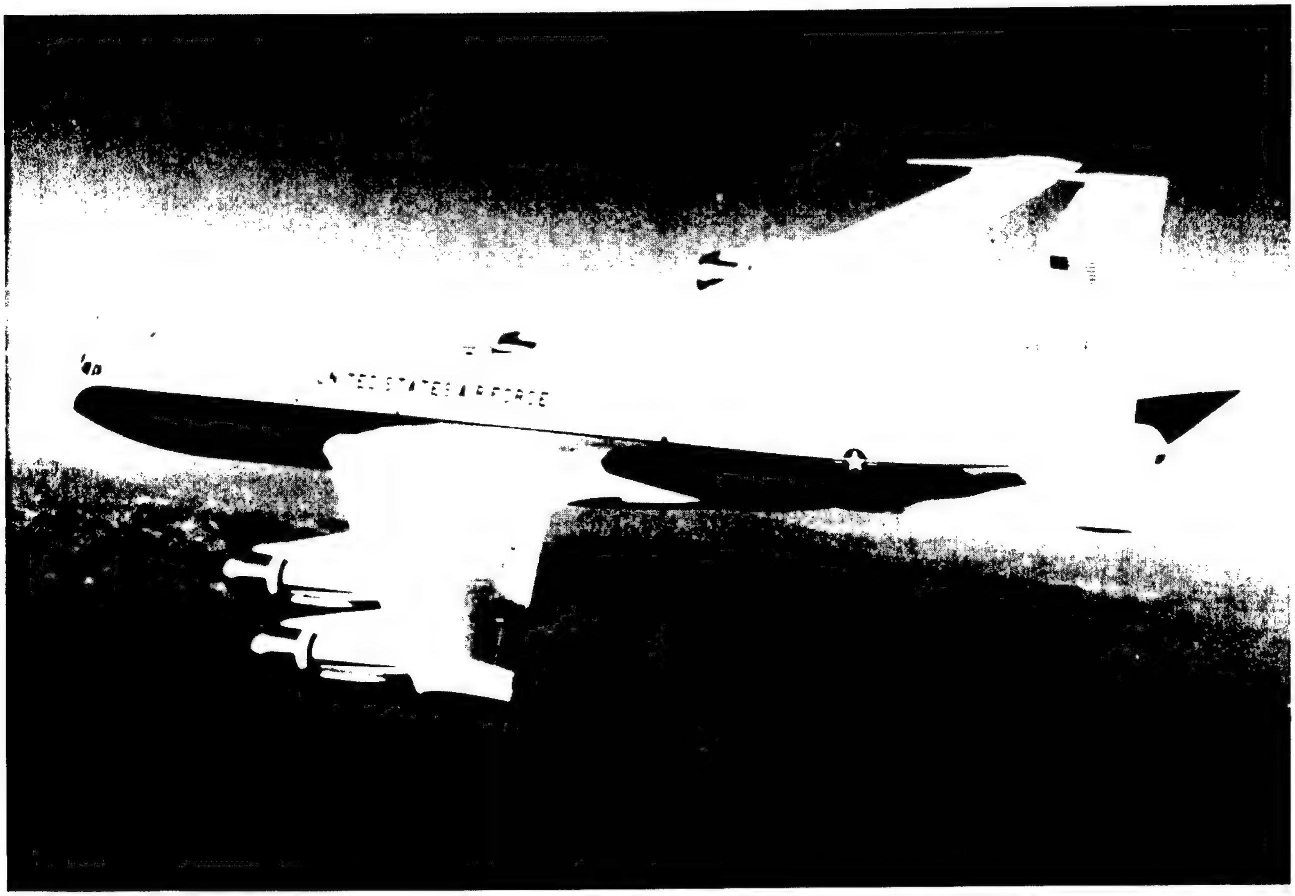
Display information provided to the pilot during an early TACS study.

Guest pilots are brought in to help evaluate new concepts studied by TACS researchers.

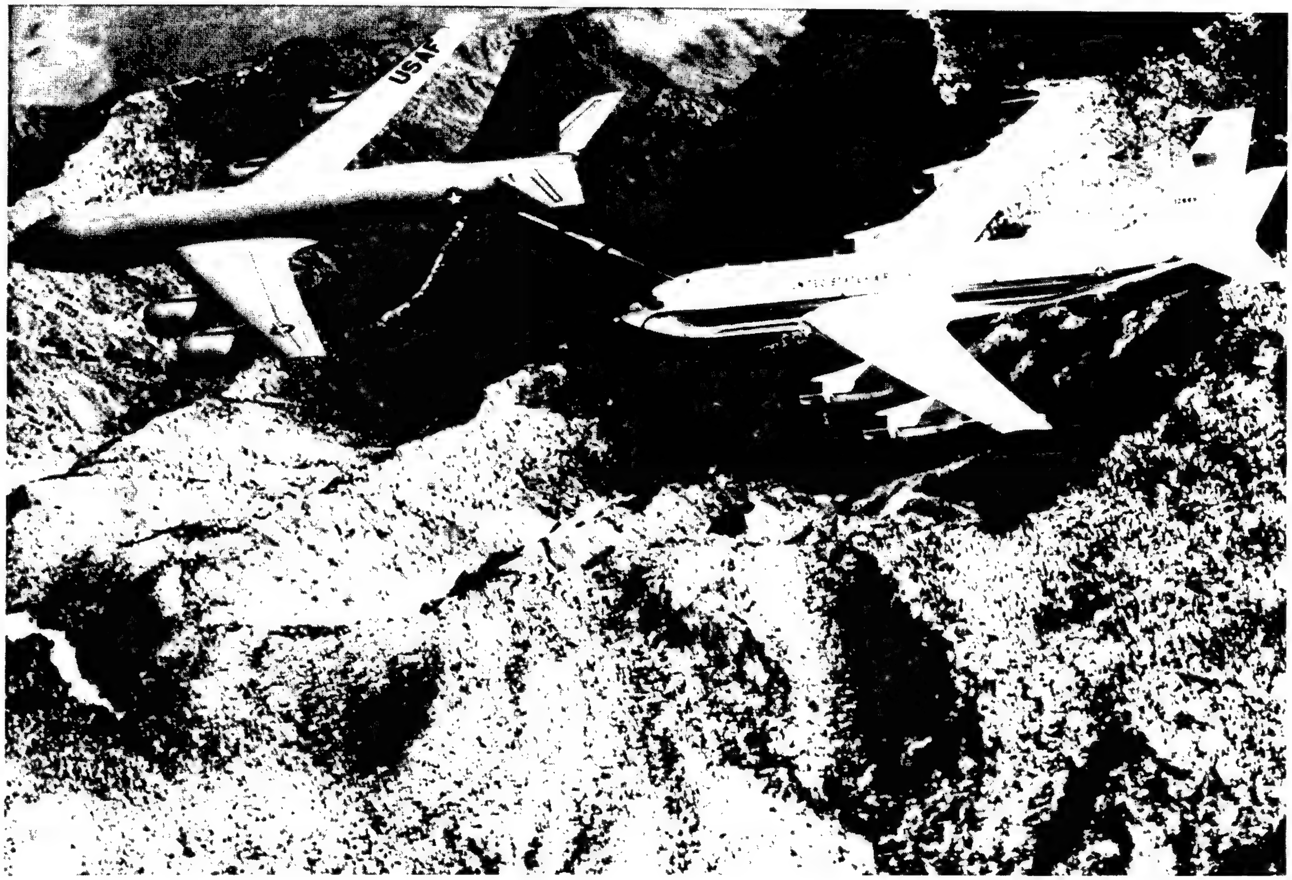


Before the invention of CRTs and pictorial displays, slide projectors provided display formats for simulators.

KC-135 tanker, and established a record for the longest flight test ever conducted with the Speckled Trout. The aircraft has also been used extensively in testing digital flight control systems; tests are often conducted while the plane transports the Air Force Chief of Staff, to whom it is assigned for official missions.



Flight Control Division's "Speckled Trout," a C-135 test vehicle.



The "Speckled Trout" has assessed many different flight control technologies for large aircraft.

VEHICLE SUBSYSTEMS DIVISION
FIE

PROTOTYPE FLIGHT COOLER DEVELOPMENT OFFICE (FIEC)

ENVIRONMENTAL CONTROL BRANCH (FIEE)

- ADVANCED THERMAL MANAGEMENT
- ENVIRONMENTAL RELIABILITY

AIRCRAFT LAUNCH AND RECOVERY BRANCH (FIEM)

- LANDING GEAR SYSTEMS
- SPECIAL PROJECTS

AIRCREW PROTECTION BRANCH (FIER)

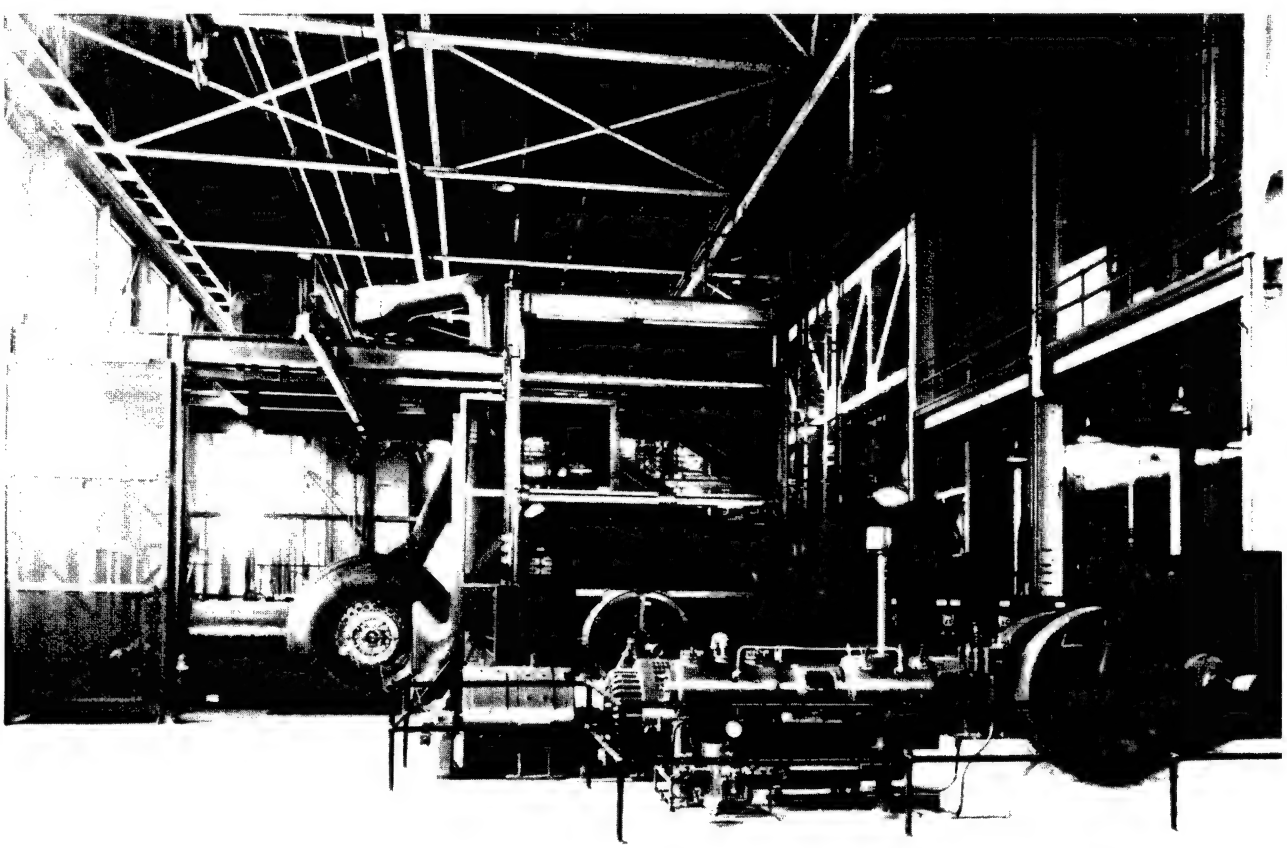
- AIRCREW ESCAPE
- AIRCREW ENCLOSURE
- AIRCREW AND WINDSHIELD PROGRAM OFFICE

SURVIVABILITY ENHANCEMENT BRANCH (FIES)

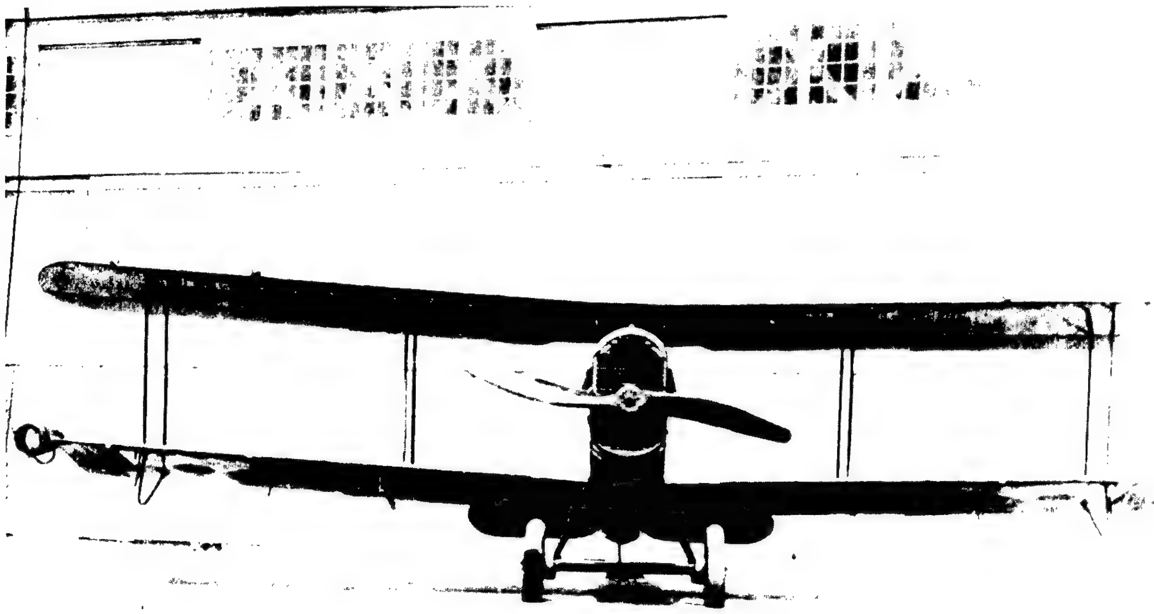
- TECHNOLOGY ASSESSMENT

Vehicle Subsystems

The division formerly known as Vehicle Equipment and its predecessors have been responsible for the safety and comfort of the crew and for certain mechanical subsystems, including airframe bearings and landing gear. In the early days, aircraft equipment was usually adapted from some existing source: automobile batteries, for example, or navigation lights from boats. McCook Field and the Airplane Lab led the world in the development of vehicle equipment created especially for "air machines." A major accomplishment of the early twenties was the adaption of the automobile self-starter for use as an airplane ignition system. Weight was reduced and torque was increased, "to the point where it could 'crank' an engine, whose power is twenty times that of the ordinary 'Lizzie'." Flares and searchlights were developed to facilitate night landings, and a nineteen-and-a-half foot silk parachute was designed. The Airplane Lab was also responsible for aircraft armaments, and worked with the Department of Agriculture to develop crop-dusting techniques. Tires, wheels, brakes and shock struts were being developed and tested at McCook Field as early as 1926, and this work has been continued in unbroken sequence by FDL.



Early tire test in Landing Gear Facility.



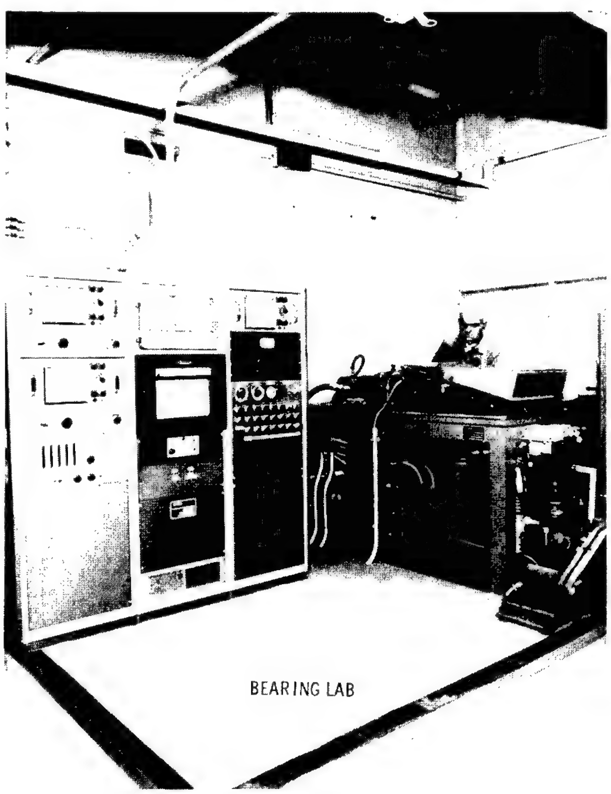
DeHavilland DH-4, used at McCook in 1922 to test landing lights. An original forerunner of today's subsystems development process.

Drafting room at McCook, where batteries, instruments and safety equipment were designed.

This chapter covers such technologies as bearings, landing gear, crew stations and escape, aerodynamic decelerators, environmental and thermal control, as well as current developments like the Combined Environment Reliability Test (CERT) program.

Bearings

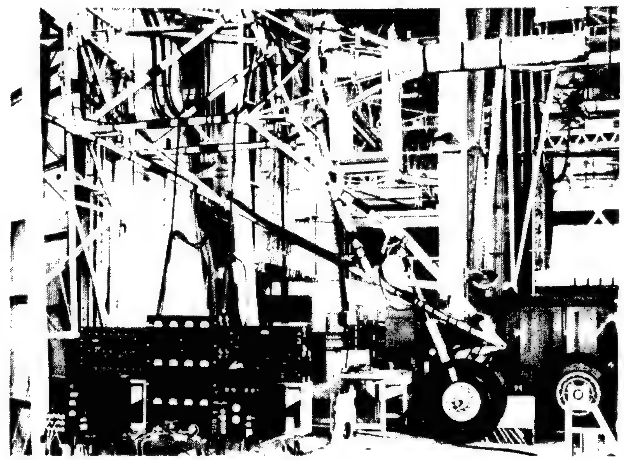
Over the years the Lab has made many contributions to bearing technology. In 1952, for example, staff engineers designed a single row roller bearing which became standard on more than 90% of the military aircraft in use during the following two decades. They also developed accessory bearings for supersonic aircraft, with accompanying lubrication systems. Bearings used in many helicopters and for high temperature supersonic and hypersonic applications resulted from studies conducted in the late fifties and early sixties. Bearings designed at the Lab which run on hydrodynamic films are used in the Titan and Polaris missiles.



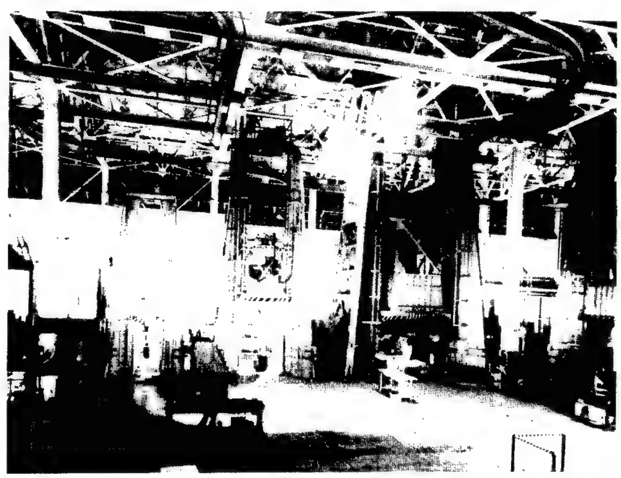
The Bearing Lab in the 1960s.

Landing Gear

Between 1951 and 1963 the Lab made a large number of minor improvements in landing gear technology, and pursued several studies on the problem of landing on extraterrestrial surfaces. Tire construction and tread design for conventional landing gear were improved, allowing for greater safety and survivability on wet or icy runways.

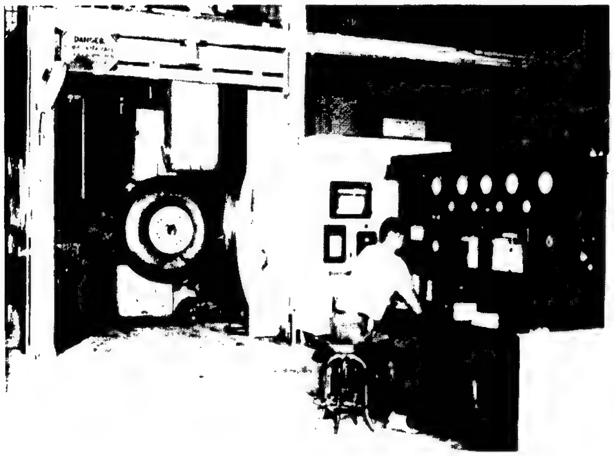


Landing gear test rig in Building 31.

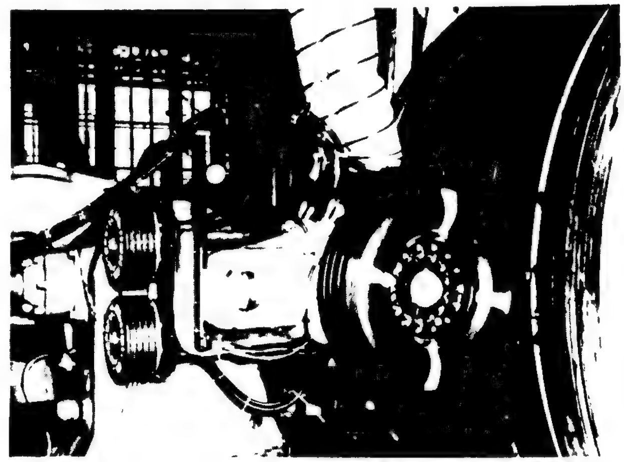


Vertical impact machines used to investigate the forces impacting on landing gear assemblies during landing.

The rapid increase in aircraft speed and performance in this period also required better friction coefficients for brakes and tires; this was

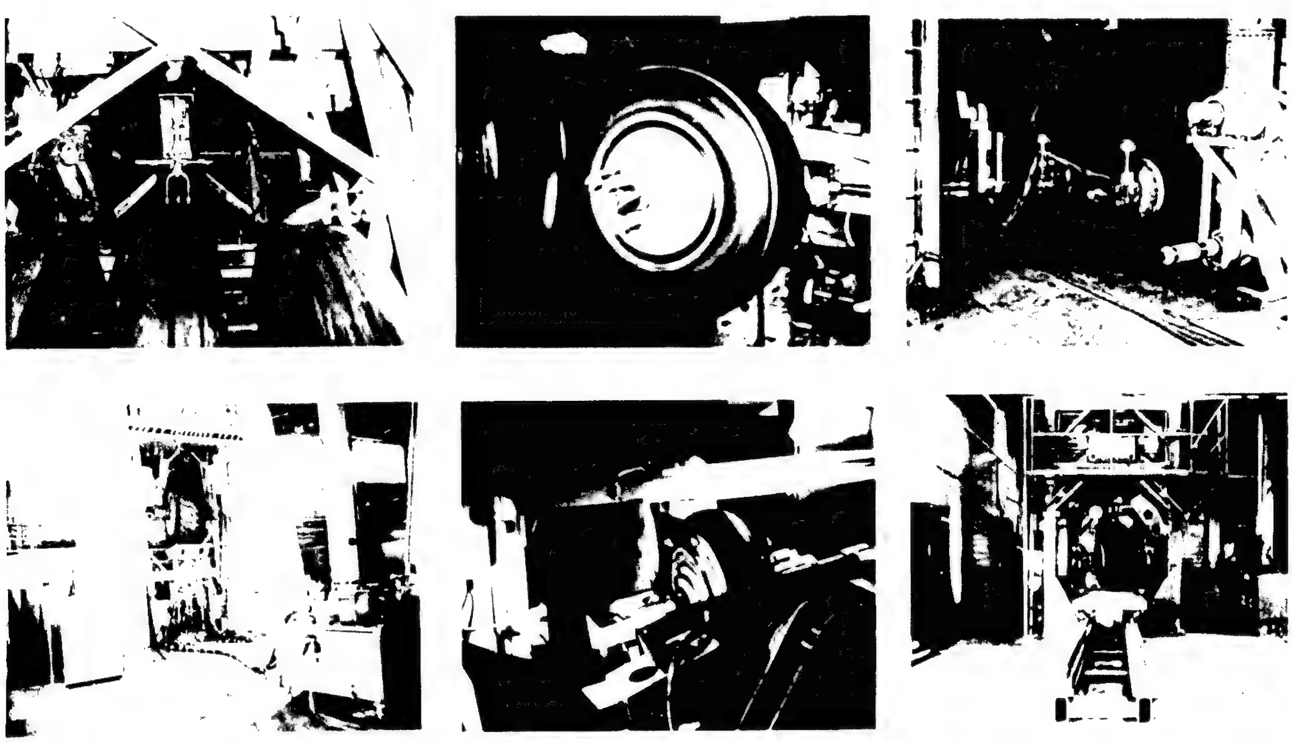


A technician conducts a test with the tire test dynamometer.

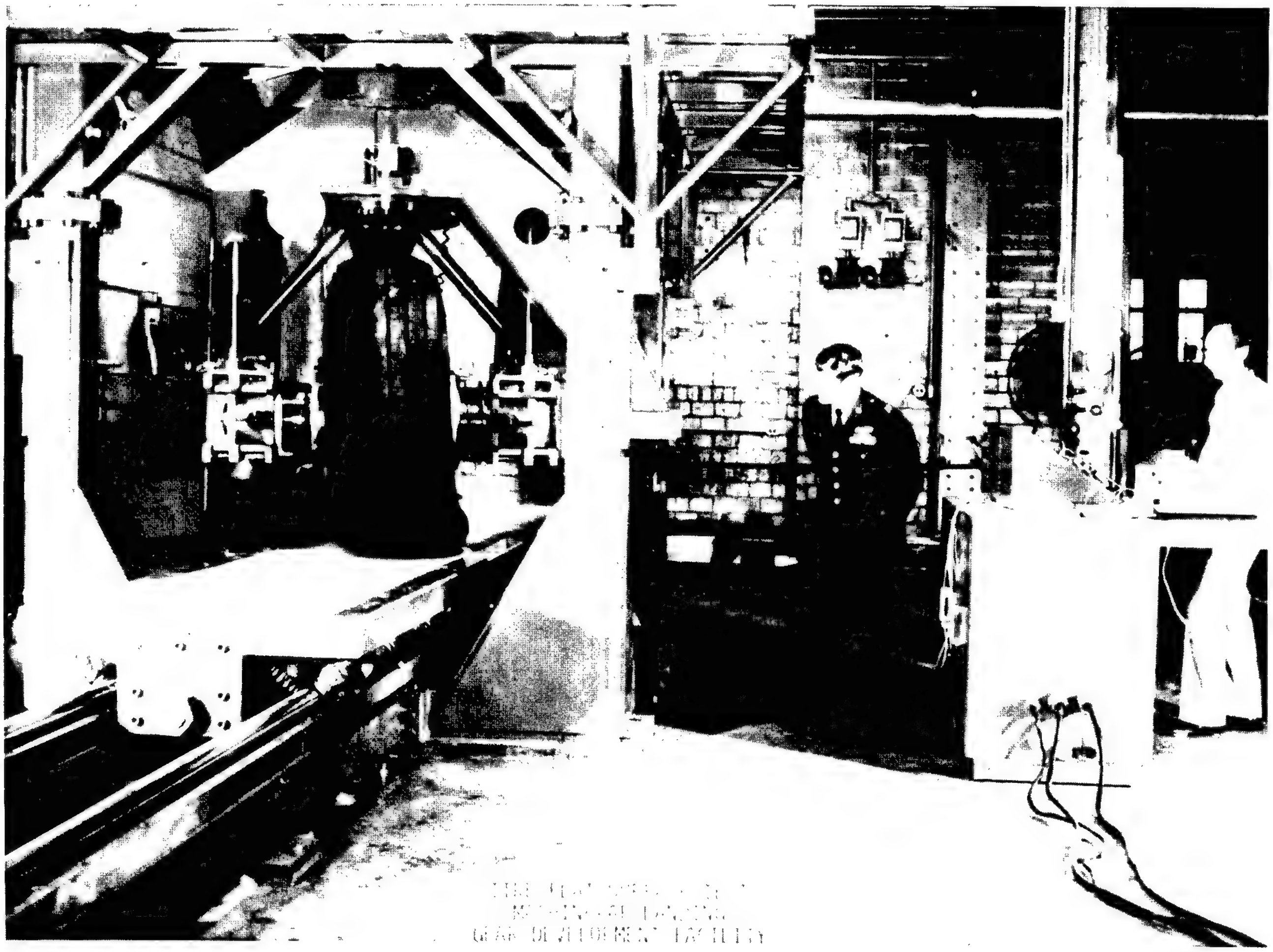


Tire test dynamometer, using a large weighted flywheel to simulate the inertia of the aircraft. The brakes must be able to overcome this inertia to stop the plane.

accomplished through the substitution of disc brakes for drum brakes. Anti-skid devices with anti-lock circuits and automatic braking systems were designed and tested. These changes were incorporated into most bomber and fighter aircraft developed after the late 1950s. Studies were also conducted to obviate such problems as brake chatter and squeal, and advances were made in prediction of vibration coupling characteristics. Lab engineers succeeded in reducing the stowage space for retracted landing gear and reduced the size and weight of



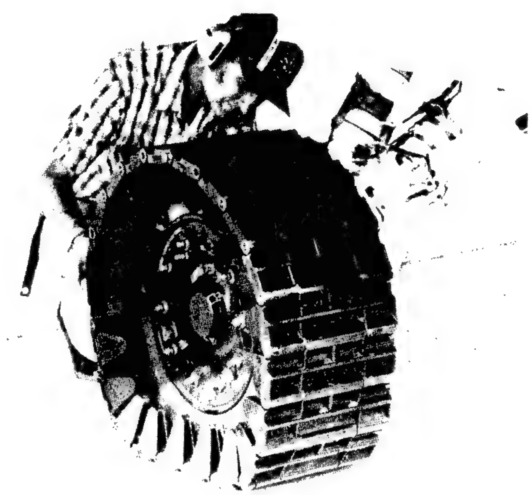
Composite showing the broad range of hardware maintained by the Landing Gear Test Facility.



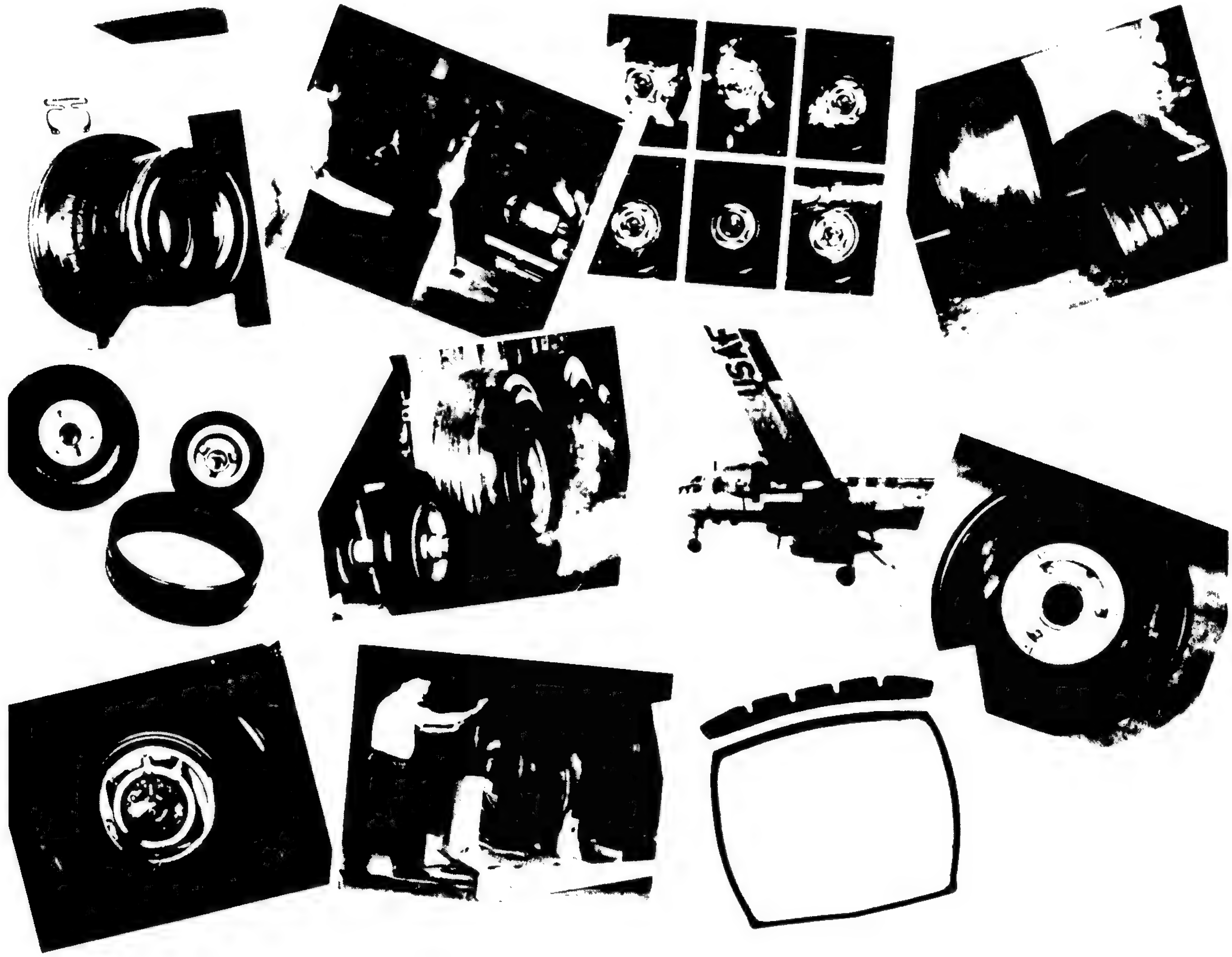
The tire flat surface test machine imparts side forces (loads) to aircraft tires, and tests the effects of different surfaces.

components such as shock absorbers. Steering systems were improved through exhaustive studies of shimmy damping devices, and the effects of trail, camber and yaw were considered in creating new designs. Most modern bombers, cargo aircraft and fighters now use landing gear steering systems developed at Wright Field.

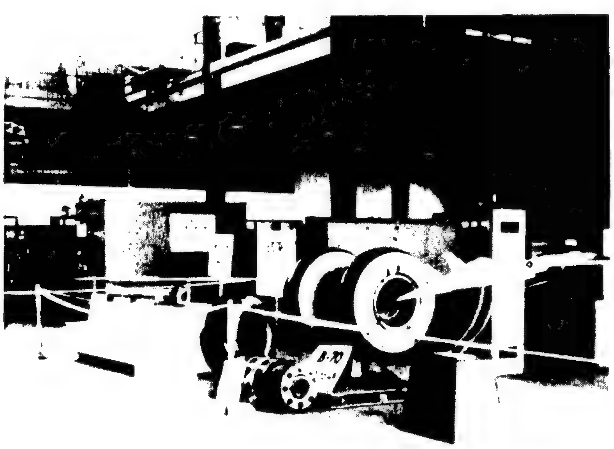
Through evaluation of improved materials and reflective coatings, the temperature capability of high performance landing gear tires was raised significantly. This new technology was especially useful for supersonic craft such as the X-15, B-70 and YF-12. Novel methods of reducing tire temperature were also explored. For example, it was discovered that low emissivity coatings on the inside of the wheel well could reduce high temperatures. This



Track device attached to aircraft tires during taxiing over soft ground. It is detached before takeoff.



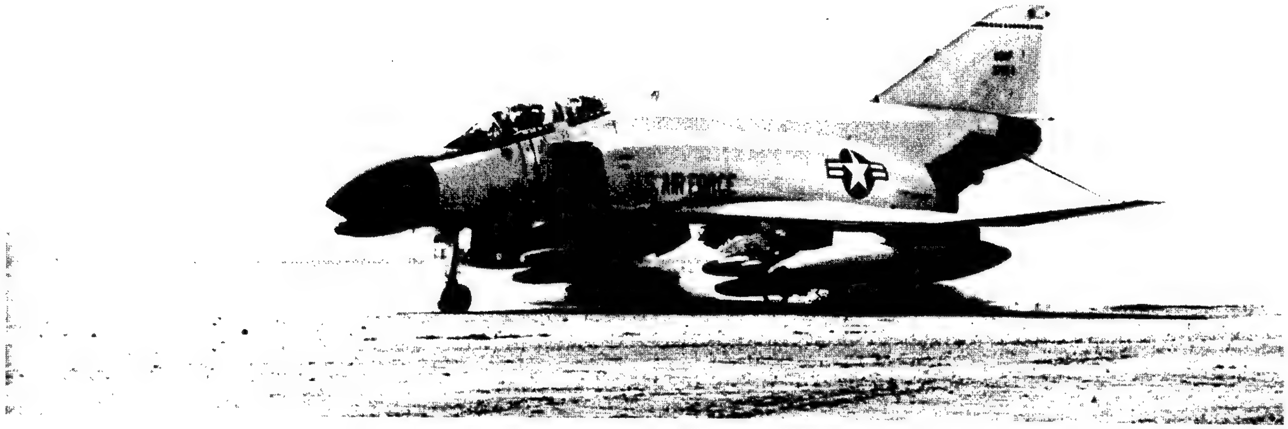
Many tire and brake concepts have been tested in Building 31, a "national" research facility.



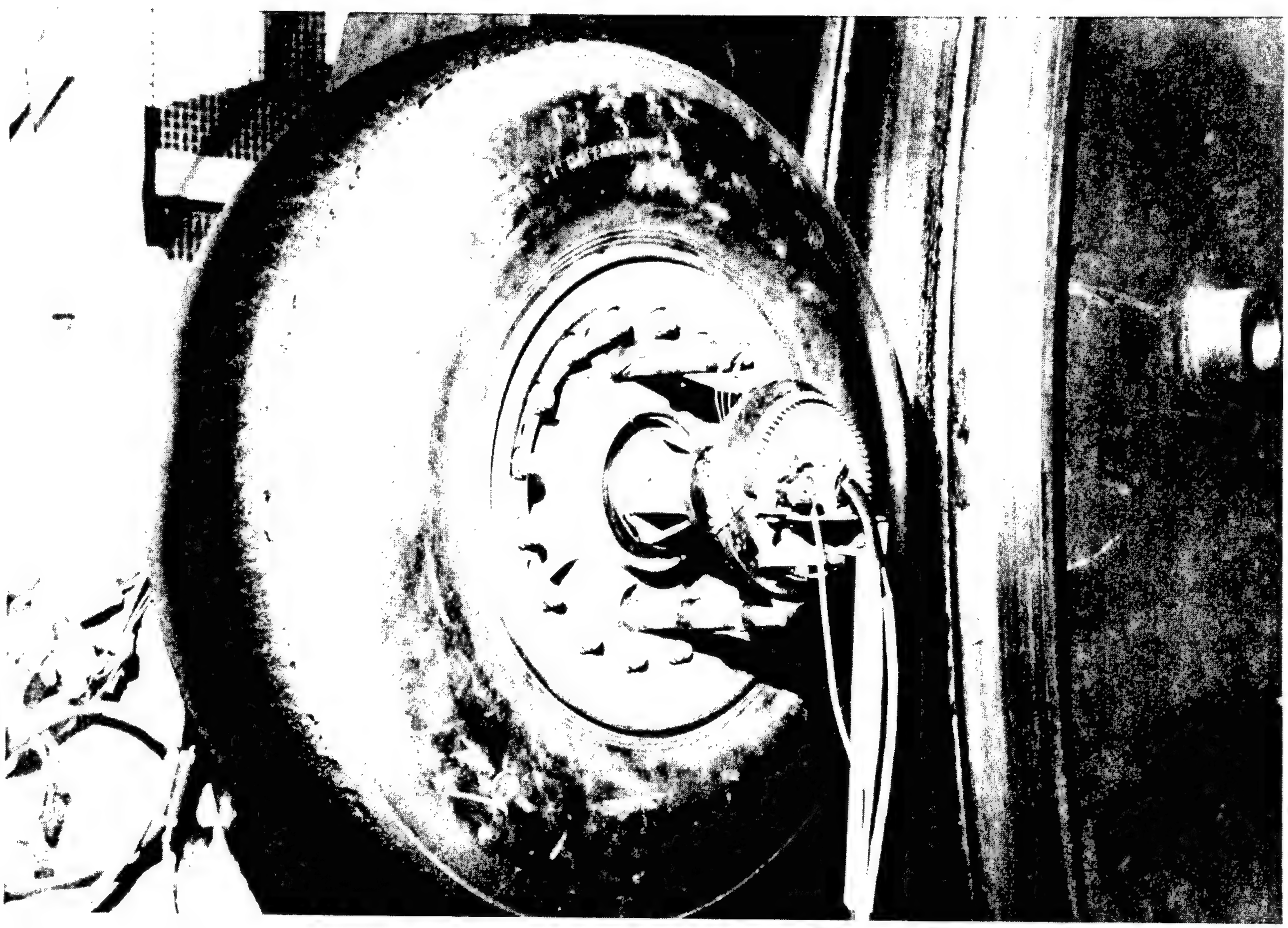
Research and development on the XB-70 landing gear included painting the tires silver, to help dissipate heat buildup in the wheel wells.

technology was essential for the development of SST and hypersonic vehicles tested later in the 1960s, and is again being used as hypersonic glide vehicle research is renewed. To accommodate extreme temperatures in future recoverable re-entry vehicles, wire brush tires and wheels capable of withstanding 1000 degrees Fahrenheit have been developed. Considerable effort also went into improving the flotation capabilities of aircraft undercarriages.

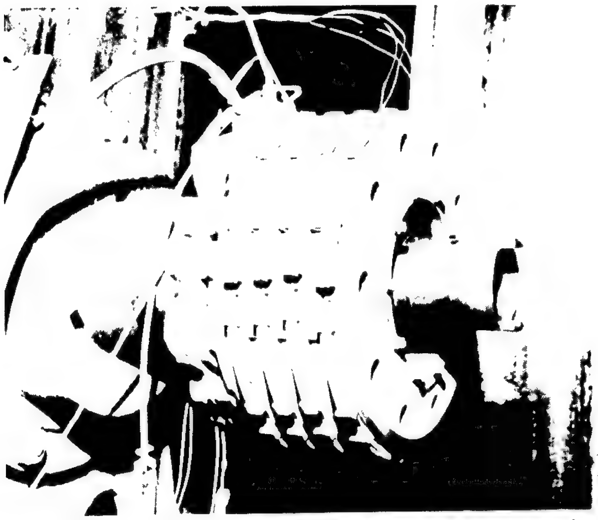
The old Unit Construction Index method, used to predict landing gear response capability on unpaved surfaces, was replaced with the more effective California Bearing Ratio method. In 1964 the new FDL continued this work, with the C-5A and similar aircraft in mind. The



Fully loaded F-4 conducting soft field taxi tests.

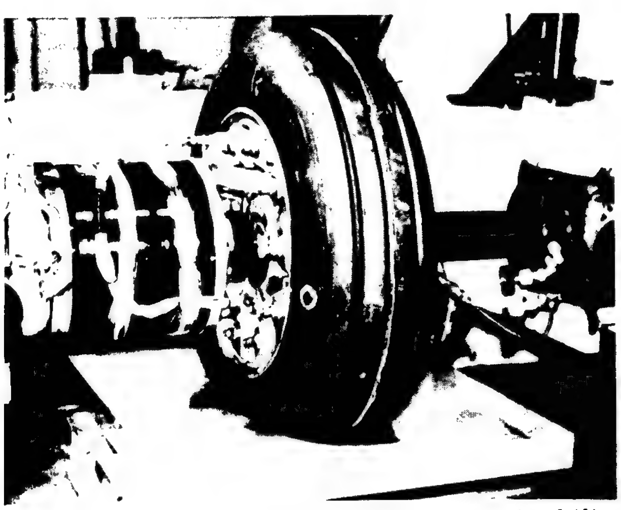


Beryllium brake assembly, an example of the many materials used in wheel and brake research.



Beryllium brake assembly mounted on a typical test mandrel.

Mechanical Branch of the Vehicle Equipment Division now also took responsibility for research in airframe bearings, space vehicle orbital rendezvous and docking, in addition to landing gear subsystems. During the late sixties the branch investigated boron fiber composites and filament-wound tubular sections as weight-reducing substitutes for metallic landing gear components. Two test facilities -- the Bearing Laboratory and the Branch Landing Gear Development Facility -- were then in use.



A program to improve reliability, maintainability and supportability of wheels is under way at FDL.

Air Cushion Landing System

An investigation of the air cushion landing gear concept, begun in a small way at the Mechanical Branch in 1966, became a major project in the following decade. The air cushion concept is based on the ground effect principle which employs a layer of air instead of wheels as the aircraft ground contacting medium. This concept was suggested by the Air Cushion Vehicles which are now being used throughout the world for transporting heavy loads across soft ground.

Not all landing systems rely on wheels. This C-130 aircraft has air-cushion landing gear for rough field operation.

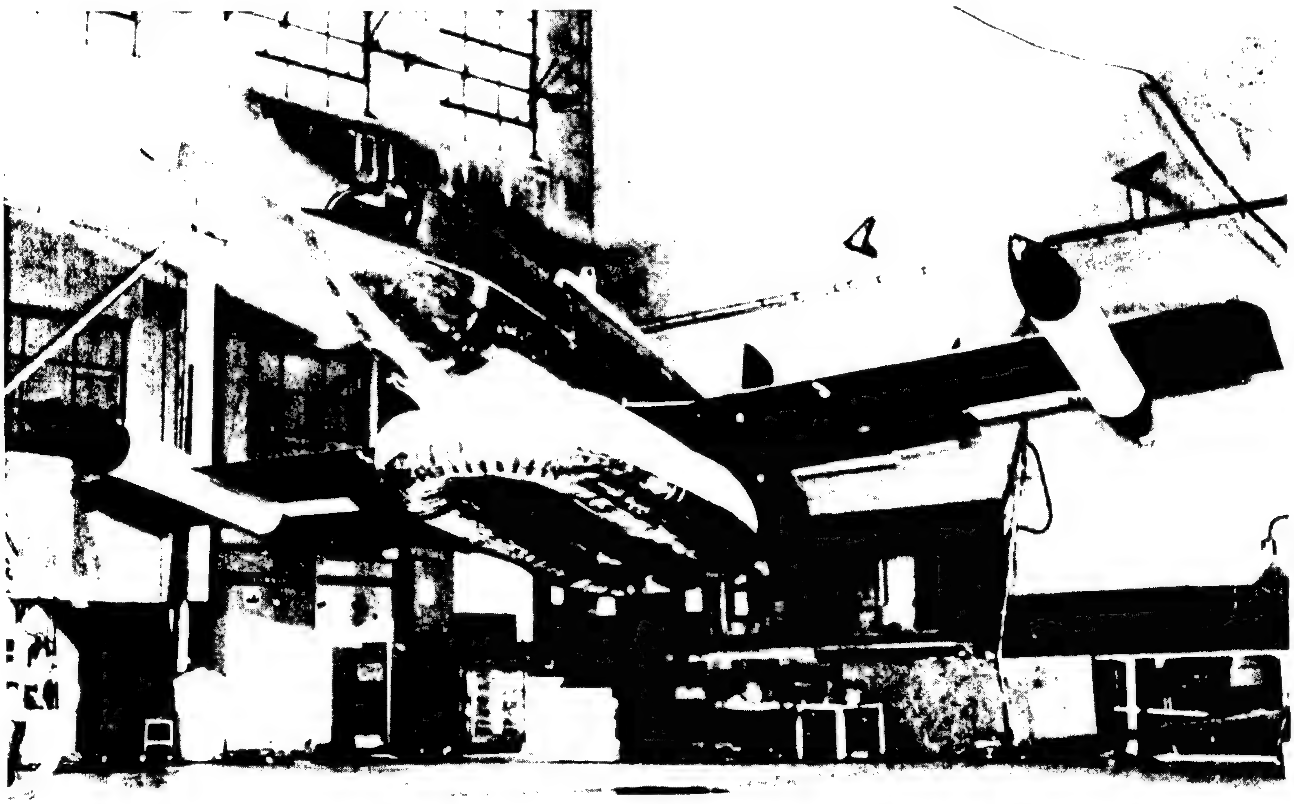
The ACLS employs a large expandable tube, over three feet in diameter when inflated, which encircles the bottom of the fuselage providing both an air duct and seal for the air cushion. The bottom of the tube, which is called the trunk, contains holes through which low pressure air passes into the air cushion cavity. The air source for the system is an onboard auxiliary turbine-driven fan. The low pressure within the cushion cavity -- about one pound per square inch -- multiplied by the platform area produces a force equal to the weight of the vehicle. Due to these low ground overpressures, the aircraft can operate from extremely soft surfaces, including water, and the flexibility of the rubber trunk allows the vehicle to ride at a very low ground clearance. Prior to the use of trunks, a substantial

Conceptual transport utilizing an air cushion concept to increase lift-off weights and permit operation on rough or bomb-damaged fields.

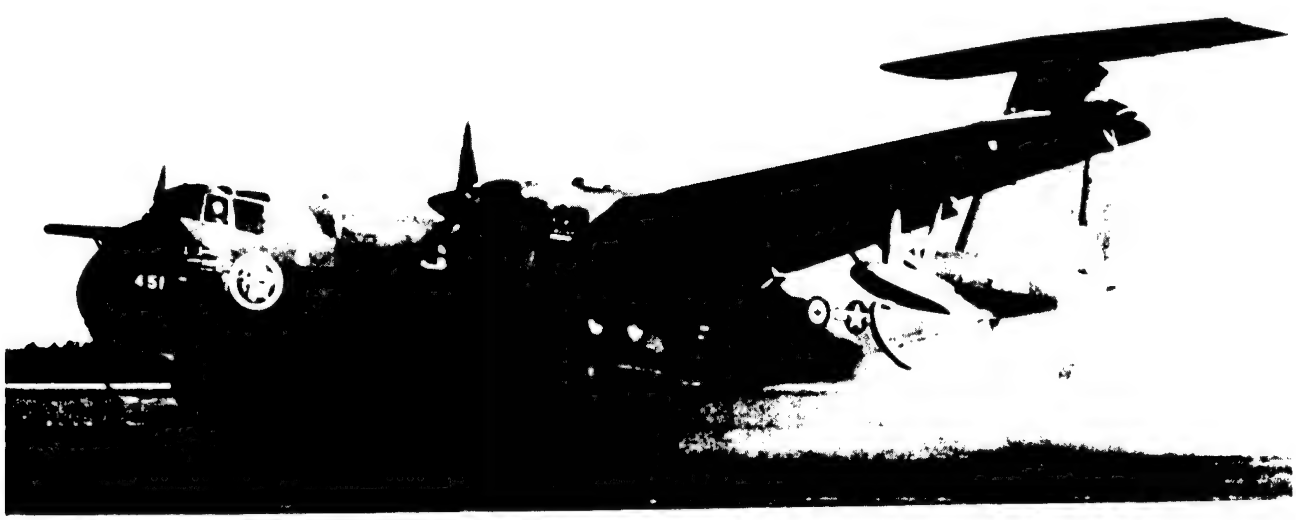
power requirement approaching that of a VTOL aircraft was necessary to provide a practical hoverheight distance between the ground and the vehicle hard structure. The use of the flexible trunk significantly increases the hoverheight, allowing the vehicle to traverse obstacles up to two-thirds of the trunk depth without increasing the clearance and lift power.

The Flight Dynamics Laboratory began investigating the feasibility of applying the ACLS concept to Air Force aircraft with an initial wind tunnel and dynamic model test program. Flight testing followed, on a 2500-pound gross weight Lake LA-4, dramatically demonstrating the unique capabilities of this landing system for routine operation on snow, ice, rough terrain and doughy mud strips, even under high crosswind conditions. As a result of the successful LA-4 tests, the USAF and the Canadian government initiated a joint cooperative development project in May 1971 to demonstrate the functional capabilities of an ACLS-equipped De Havilland Buffalo aircraft, designated the XC-8A and weighing 41,000 pounds. Also during this period the USAF and the Australian government investigated the application of an ACLS for advanced remotely piloted vehicles. This program included both model wind tunnel testing and ground testing of a full-scale, 3800-pound gross weight Jindivik drone.

The Air Cushion Landing System represents a technological breakthrough in aircraft design,



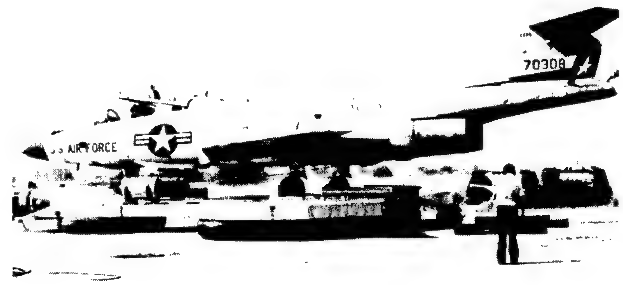
Remotely piloted vehicle, part of a joint program with Australia to test an early air cushion concept.



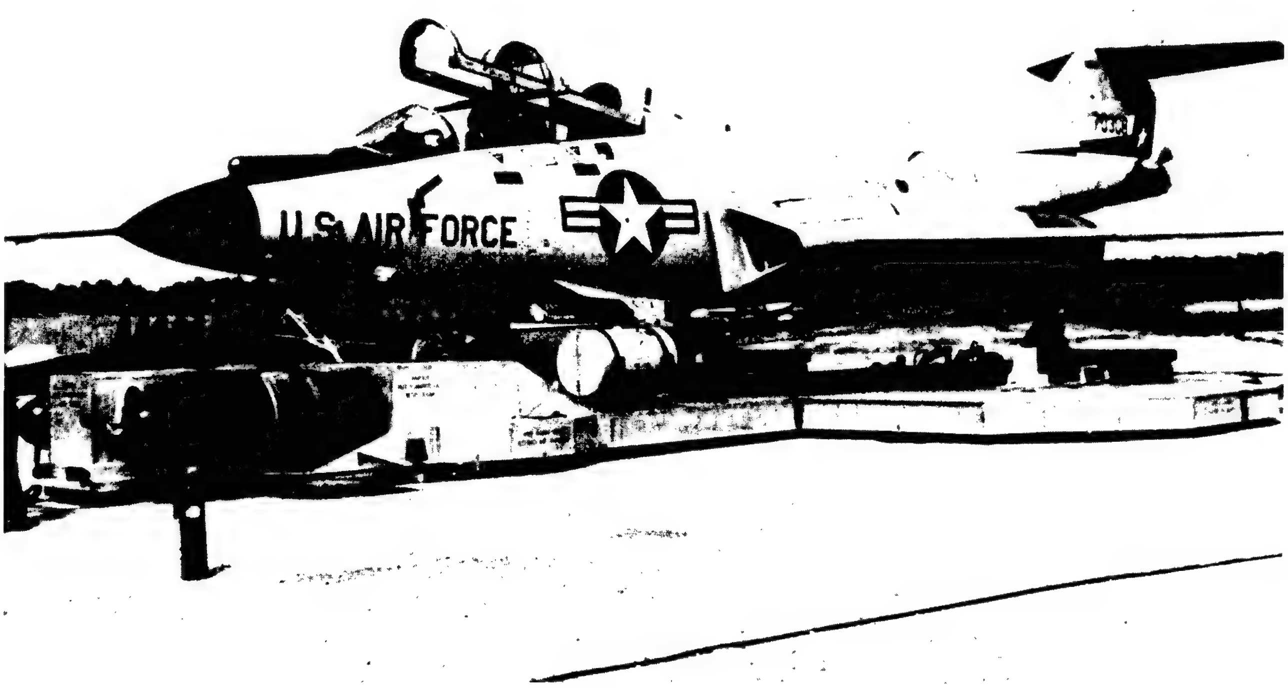
This DeHavilland XC-8A Buffalo aircraft was part of a joint flight test program with Canada, to test an air cushion landing system.

and these test programs provided the first tangible information on operational performance, maintenance, and crew training. In the end, the project was discontinued because compressors with the required power were difficult and costly to build. Such compressors are now cost-effective. The ACLS technology is available if funding is again applied.

A valuable spinoff, however, was the Air Cushion Equipment Transporter (ACET), a joint USAF/Canadian project. ACET is a towed, air cushion supported platform capable of moving aircraft or other equipment weighing up to 60,000 pounds across rough or soft ground. The prototype ACET is now being used at Davis Monthan AFB for this purpose.



Air cushion emergency transport vehicle towing an F-101 over soft ground, in a demonstration in Canada.



Air Cushion Equipment Transporter (ACET), another US-Canadian project. The ACET is still in use at Davis-Monthan AFB.

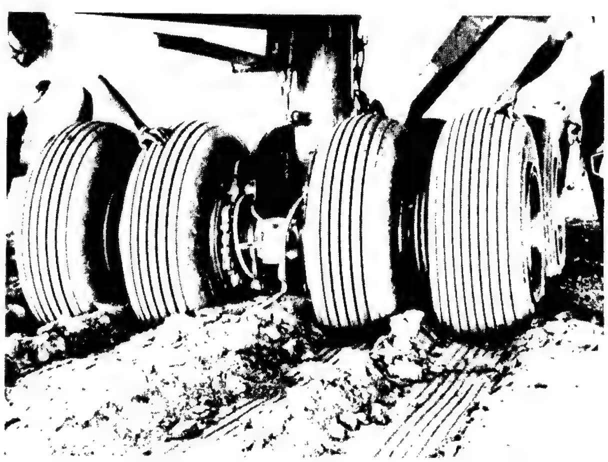
Testing for foreign object lofting by F-4 nose landing gear tires. Aircraft landing on debris-strewn, bomb-damaged runways are susceptible to this phenomenon.

Conventional Landing Gear Technology

During the 1970s a number of structural carbon brake heat sink systems from various aircraft brake companies were evaluated in the Landing Gear Development Facility. Experienced gained from these laboratory evaluations provided insight into the advantages and problems associated with the implementation of carbon brakes, which absorb heat more efficiently than older systems. Also, testing techniques were developed to provide a realistic service life-spectrum type laboratory qualification. These techniques are still used today to evaluate carbon aircraft brakes. Carbon brakes are now used in all new high performance military aircraft. In addition, many innovative tire designs were developed through FDL-sponsored contractual programs. These programs included the Expandable Aircraft Tire (1964-73), the Rotational Mold Cast Tire (1974-79), the Radial Ply Aircraft Tire (1978-present), and the Soft Field Tire (1982-85). The radial tire has been the most successful and widely applied of these concepts. It was extensively evaluated in the Landing Gear Development Facility, starting in 1978 with the evaluation of an experimental radial design for the Mirage main tire. In the early to mid eighties, radial tire retrofits were laboratory qualified for

This F-16 tire shows how much of a drag soft field operations can be.

the F-4, F-16 and A-10 main wheel sizes. These radials were lighter in weight and offered improved durability over their standard bias-ply counterparts. Radial tire technology has been applied to the F-15E aircraft. It was estimated in 1988 that radial tires will result in a 12% to 21%

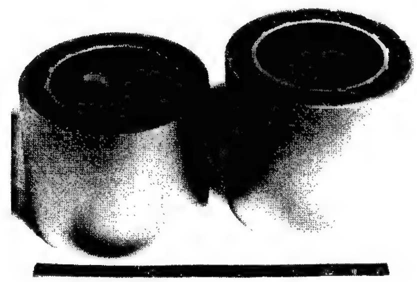


C-5 soft field operations, conducted at Harper's Lake, California. The rutter phenomenon is typical.

lighter tire with a lifetime two and a half times that of a standard tire. Both maintenance and survivability will be enhanced. The Branch also recently conducted an investigation into aircraft tire foreign object damage (FOD) reduction.

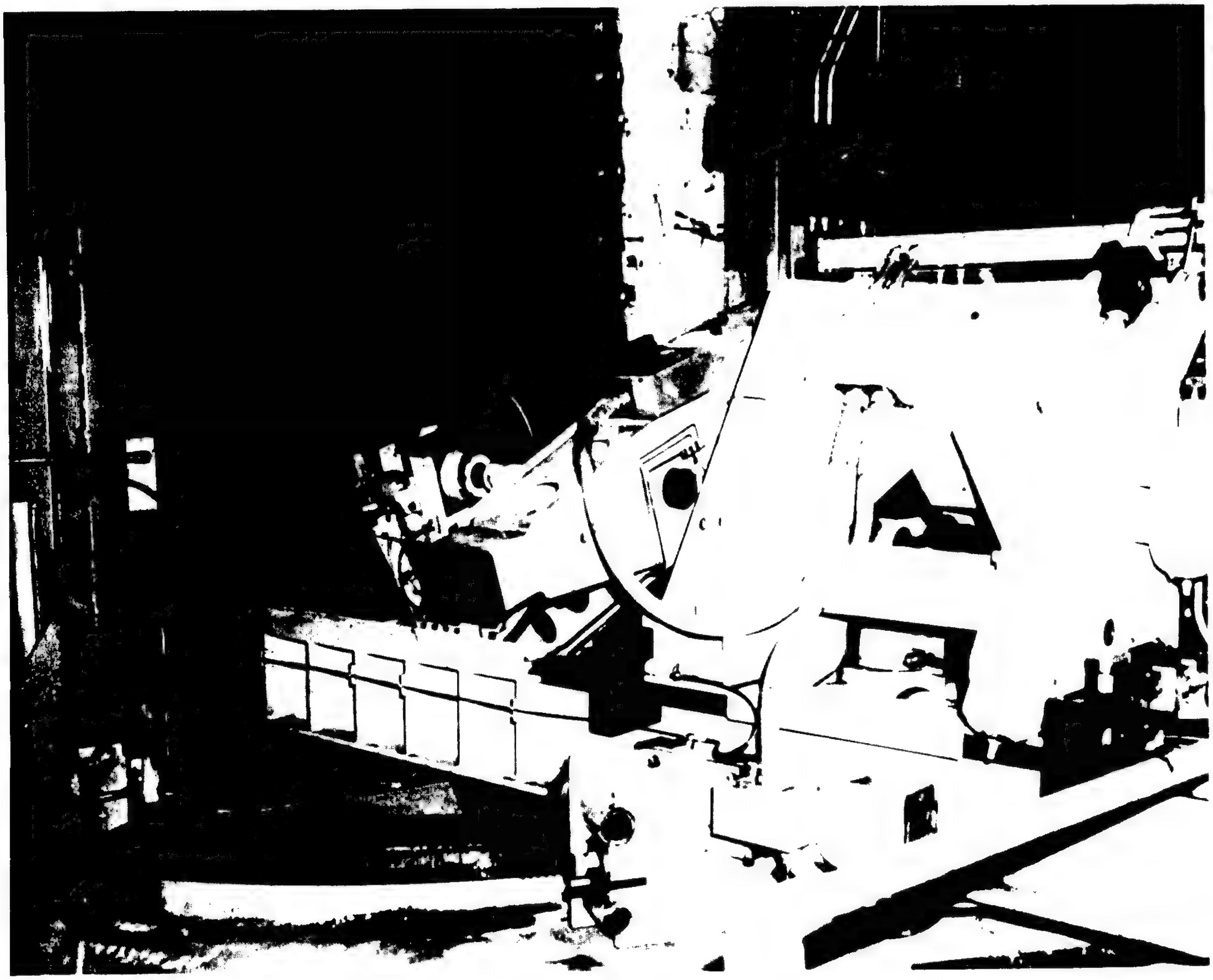
In 1978 the Landing Gear Branch explored a deployable plastic foam concept for ground impact attenuation in a remotely piloted vehicle. The Branch also completed a feasibility study of an air cushion arrestor hook landing system for an RPV. Up to that time no really satisfactory RPV landing system had been designed, but this concept provided both reduced landing loads and landing slideout distances. In 1981 the Lab demonstrated a dynamically stable ground effect take-off and landing (GETOL) system, with possibilities for future aerospace vehicle application. GETOL makes use of the "ground effect," which increases lift through interaction between the ground and the propulsion system.

After the late seventies, landing gear research concentrated on improved materials. A superplastic formed and diffusion bonded (SPF/DB) titanium sandwich cylindrical tube section was fabricated and tested. This project raised hopes for more extensive use of titanium in landing gear components, resulting in considerable corrosion reduction and weight savings.



Superplastic formed/diffusion bonded landing gear cylinders.

A decade earlier, Lab engineers had conceived the idea of a self-sensing and self-adjusting strut called an Active Landing Gear. Several studies later confirmed that the concept was workable, so in 1979 the Lab entered into a joint program with NASA to build and test such a landing gear for an F-4. The tests were successful. In the same



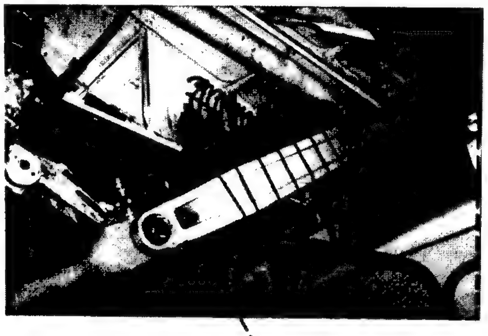
The Lab has tested elements of the space shuttle landing gear systems, and a full system will be tested in the future.

year the Branch successfully tested the landing gear system on the space shuttle *Columbia*.

Investigations were also conducted during the eighties on Alternate Aircraft Take-off Systems (AATS), to improve capability of launching fighter aircraft from battle-damaged runways. Testing for many of these concepts was conducted at the Mobility Development Laboratory facility, which contains many unique test rigs.

A dual mode adaptive landing gear was successfully demonstrated in 1982 on an L-1011 aircraft. The conventional landing gear was modified by the addition of a nitrogen strut chamber and pressure system. When the pilot switches over to the alternate system, a softer spring rate is achieved, allowing for significant load reduction when operating on rough runways. Retrofit is simple, requiring no new hardware, and the system adds only negligible weight and cost. Also in 1982, the Lab initiated development of the jump strut concept. This design featured internal energy storage which could be quickly released to extend the strut, allowing early aircraft rotation during the takeoff roll. Takeoff distances could thus be reduced by as much as 40%.

In 1985, the Landing Gear Development Facility completed evaluation of two advanced rough field gear designs for the F-15. The first



Nitrogen strut chamber installed on an L-1011 landing gear to test load reduction techniques during operation on rough runways.

system was based on an advanced passive concept and the second incorporated an internal actively controlled servo valve. This project resulted in greatly increased rough field performance without reducing reliability and maintainability.

The Branch continues to investigate soft field tire technology, and has evaluated an Integrated Aircraft Brake Control System (IABCS) which is expected to improve operation from slippery and narrow runways.

Branch engineers recently conducted a test of tire foreign-object lofting with an F-4 at Lakehurst, New Jersey. The aircraft rolled over a debris-strewn runway intended to simulate battle-damage conditions. The project demonstrated that the danger of engine damage from objects thrown up by the tires is less than expected, and new data were gathered on tire damage.

The Landing Gear Development Facility (LGDF) has kept pace with rapid advances in landing gear technology. New test equipment is continually added and old equipment is upgraded

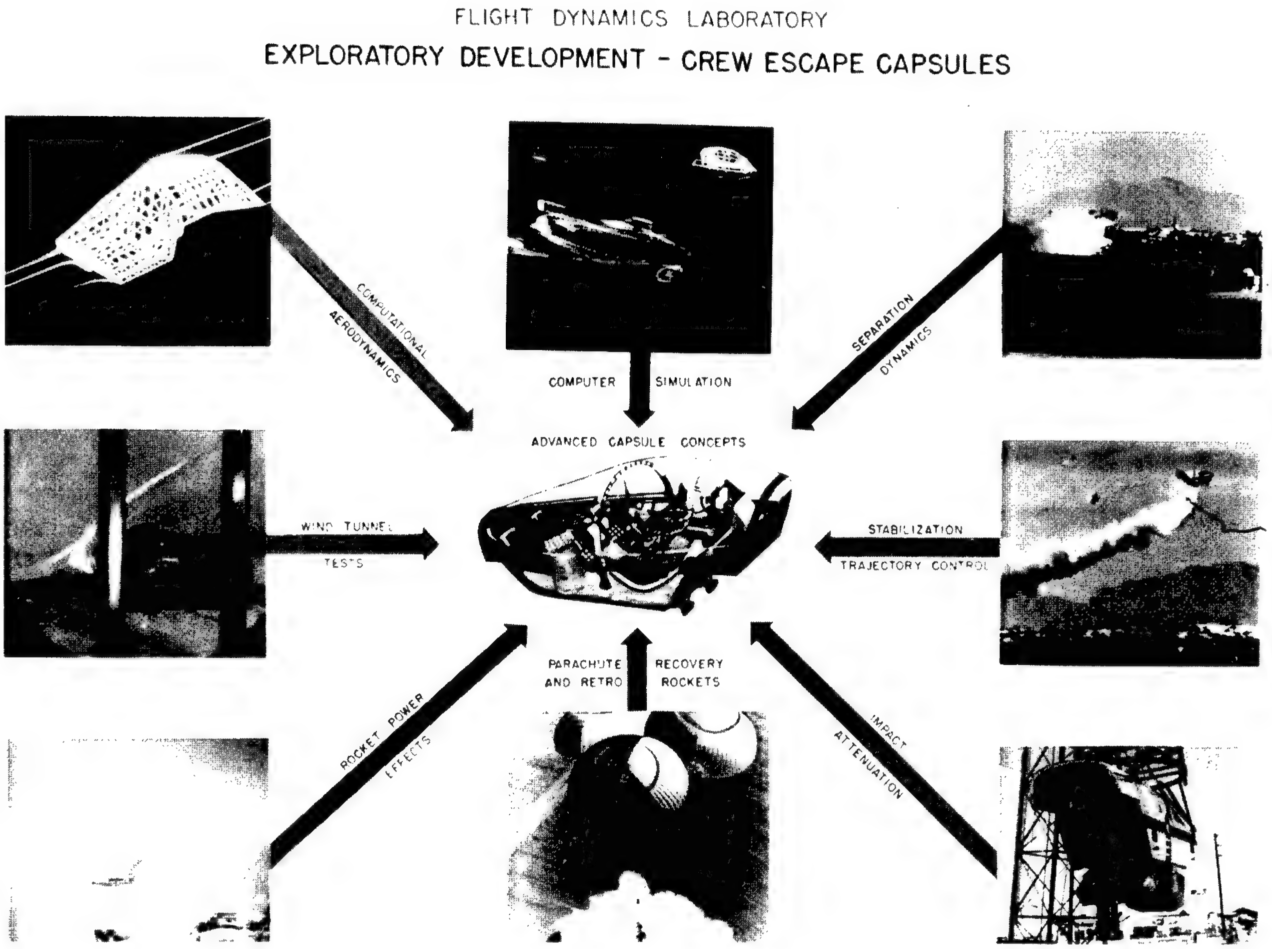
The Landing Gear Development Facility will continue to upgrade its equipment, though its location is unlikely to change.

to accommodate the increasing speeds, loads and other expanding capabilities of new landing gear systems. The LGDF is the most advanced facility of its kind in the free world. It was designated a Department of Defense facility in 1968, which means that it tests not only USAF landing gear but also supports the Navy, Army, Coast Guard, FAA, NASA, and industry, and occasionally conducts tests for our allies. At this writing, the world's largest aircraft tire-wheel-brake dynamometer (with a sixteen-foot diameter flywheel) is being modified to test the entire main landing gear of the space shuttle orbiter.

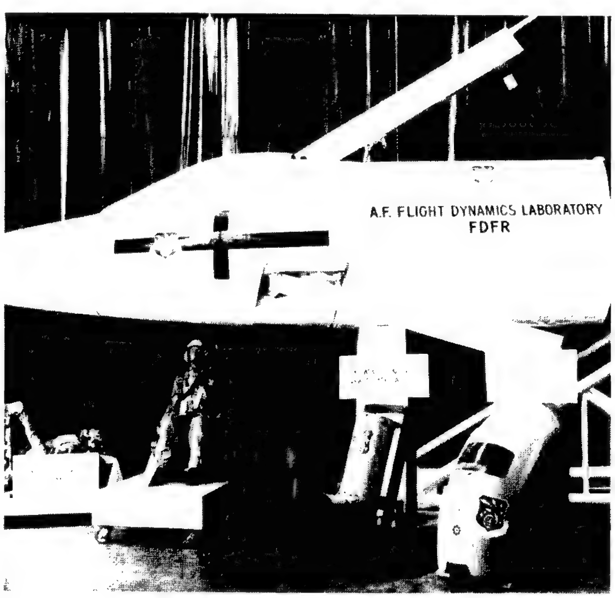
Crew Escape

One of the most valuable contributions of the Lab has been in the area of crew escape systems, an area which includes (but is not limited to) ejection seats. Cable firing mechanisms, which had proved unreliable, were replaced during the 1950s with a gas initiated catapult system. This was later developed into the standard Cartridge Actuated Device (CAD), in which the ejection seat is propelled out of the aircraft by compressed gas from a cylinder -- the same principle on which an air rifle works.

Propellant devices for crew escape systems were researched during the 1960s.



Crew escape capsules are one way of extracting the flight crew from a damaged aircraft.



Crew escape concepts displayed at a 1966 open house.

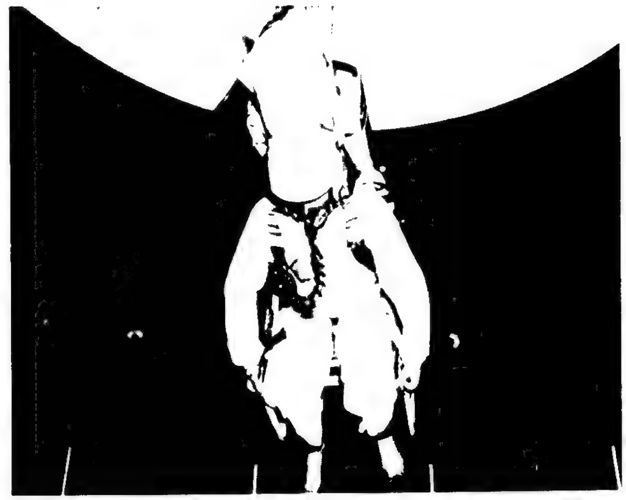
As many of the operations previously performed by the pilot (such as harness release and parachute opening) became automatic, the safe ejection altitude was considerably lowered (from 2000 feet in 1951 to 200 feet in the early sixties). Positive pilot separation from the seat was improved by such devices as the pre-tensioned survival sling which is still incorporated in ejection systems.

In the late fifties the Lab designed and built an entirely new test facility, the Supersonic Military Air Research Track (SMART), with a sharp drop-off at the end, to test ejection systems at high speeds. The F-100, F-102, B-52, B-58 and other aircraft all use ejection systems developed on this test track. Between 1955 and 1962, the Lab developed the rocket catapult for supersonic aircraft, to overcome problems such as sufficient

This dummy is given a ride during a ground level firing of an ACES II ejection seat test.

Dummies used to record the forces experienced by pilots during ejection seat tests. Dummies are cheaper, and they don't complain or demand flight pay.

clearance over the vertical stabilizer and human tolerance limits to acceleration. Encapsulated seats were developed for the B-58 and B-70, to

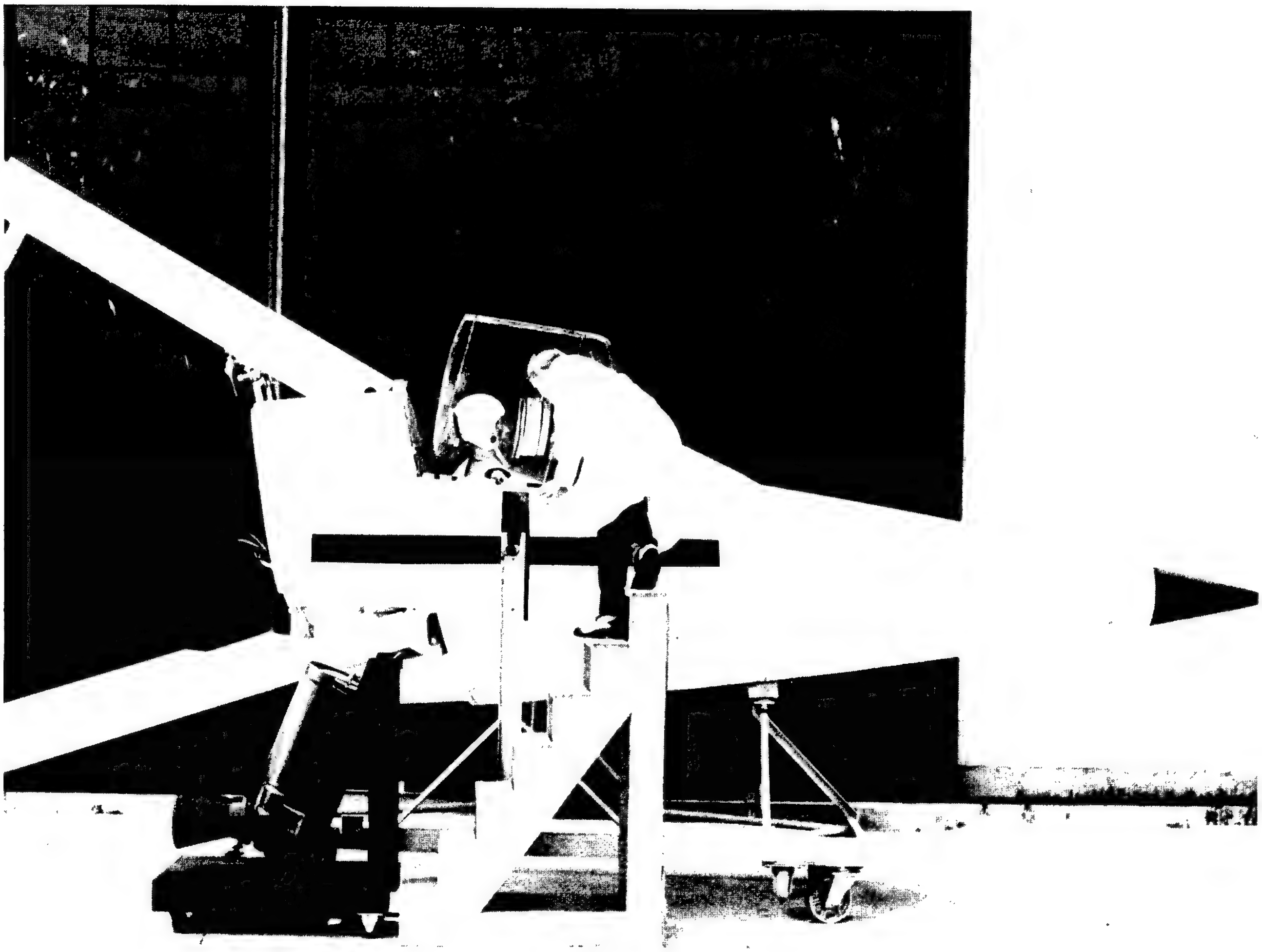


Vertical wind tunnel test of pilot/ejection seat aerodynamics.

provide safe escape above 600 KEAS (knots equivalent airspeed). In addition, the STAPAC system -- an ejection seat with a gyro-driven vernier rocket and a drogue parachute -- was developed to improve safety of ejection at low altitudes and speeds. A vernier is a small rocket used, for example, on spacecraft to make fine adjustments to the trajectory.

Between 1960 and 1963, the crew escape research team concentrated on escape from manned space capsules. Concepts applicable to low and high orbital systems, two-stage recoverable vehicles, and non-reentry systems were examined. The temperature capability of Propellant Actuated Device (PAD) systems was improved as a result of these studies. After 1963, emphasis was on low altitude escape for VTOL (vertical take-off and landing) and other low altitude, high speed aircraft. The survivability of modern fighter aircraft was considerably improved by this research.

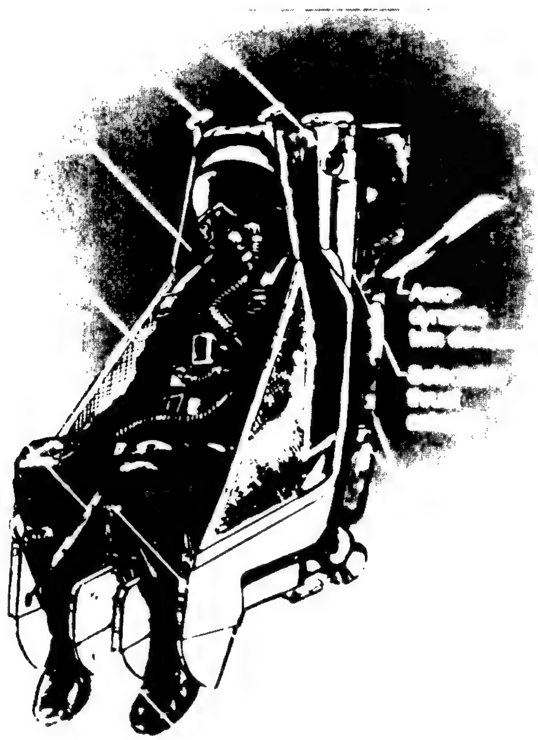
Under the FDL reorganization in 1963 responsibility for crew escape technology fell to the Recovery and Crew Station Branch. The B-1 crew escape module, incorporated into the first four B-1A bombers, was designed to provide escape for six crew members. Using a modified B-47 ejection seat, the branch explored methods of improving seat/man separation and stability. A



Full-scale nose-capsule escape system, tested to establish performance and design criteria.

full-scale ejection demonstration program of the vernier stabilizer rocket and the mortar deployed recovery parachute was conducted in the Lab. These two features are fundamental to the design and operation of the ACES II ejection seat currently used in the A-10, F-15, F-16, and B-1. In the early seventies the more theoretical aspects of ejection systems came under study. Extensive wind tunnel tests were conducted on both ejection seats and capsule type escape systems to determine the aerodynamic characteristics for analysis purposes. The SAFEST computer program was developed to conduct the escape systems' performance capabilities analysis. In order to develop prediction techniques, it was necessary to determine the center of gravity and products and moments of inertia of both occupied and unoccupied seats. Lab engineers crafted a one-of-a-kind center-of-gravity and inertia measurement device for this purpose. The Branch also explored several entirely new crew escape concepts, such as thrust vector control of the escape rocket to enhance ejection seat stability during the main propulsion rocket burning phase. Changes in cockpit design required better escape system integration, and a reclined ejection seat was developed for vehicles operating at accelerations beyond human functional capabilities while upright. In the early eighties ejection seat technologies such as controllable catapults, selectable thrust rockets, and vectored flight control systems were

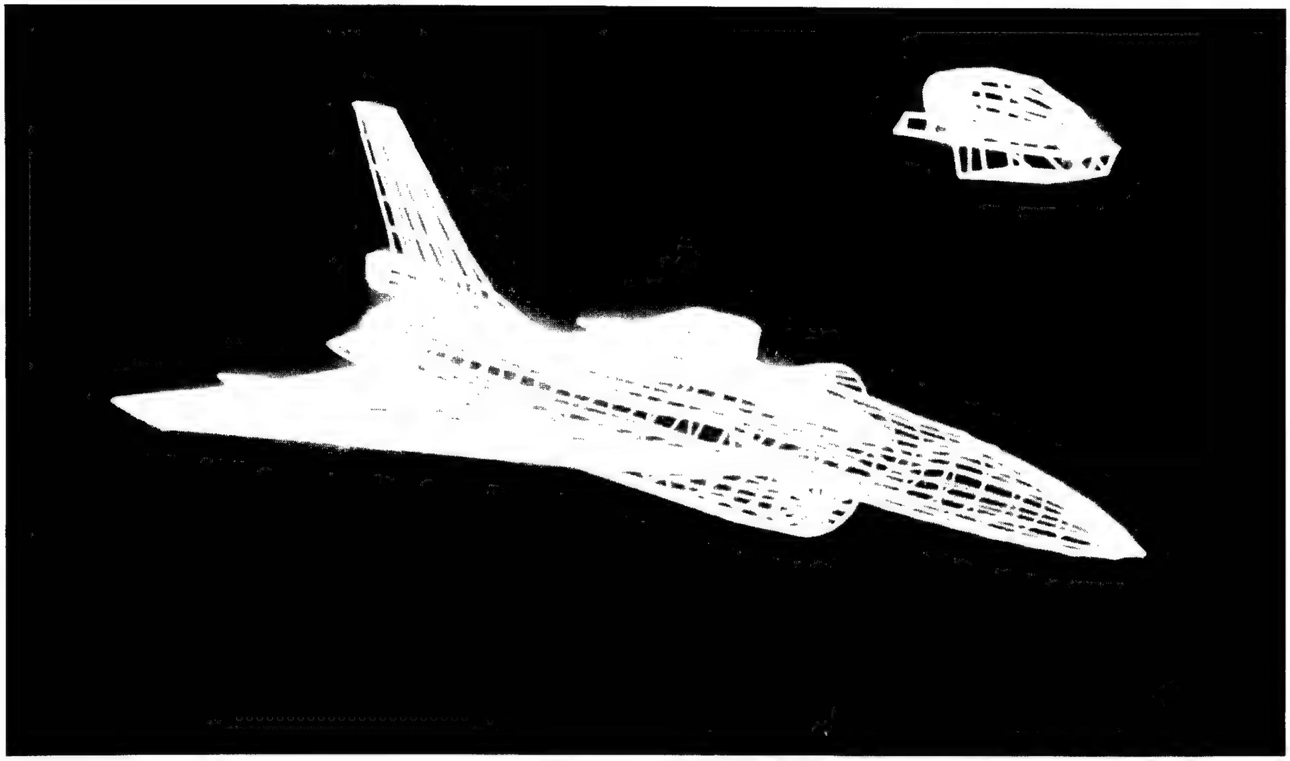
developed and transitioned to the Crew Escape Technologies (CREST) advanced development program. Currently, programs are under way to develop the technologies required to provide a



Pilot safety is always a primary concern in the design of a crew extraction system.

A full-scale nose-capsule escape system separates from a simulated fuselage section during a high-speed track sled test (up to 900 knots).

The B-1 was initially designed with a crew escape capsule concept. Following separation the capsule returned to earth by parachute.



Engineers design safer crew escape systems with the aid of computer models.

crew escape capsule for future aerospace vehicles. The Aircrew Protection Branch is presently providing support to the CREST ADPO in the areas of propulsion, flight control, and trajectory analysis. The Branch developed the controllable catapult which will be used in the demonstration program.

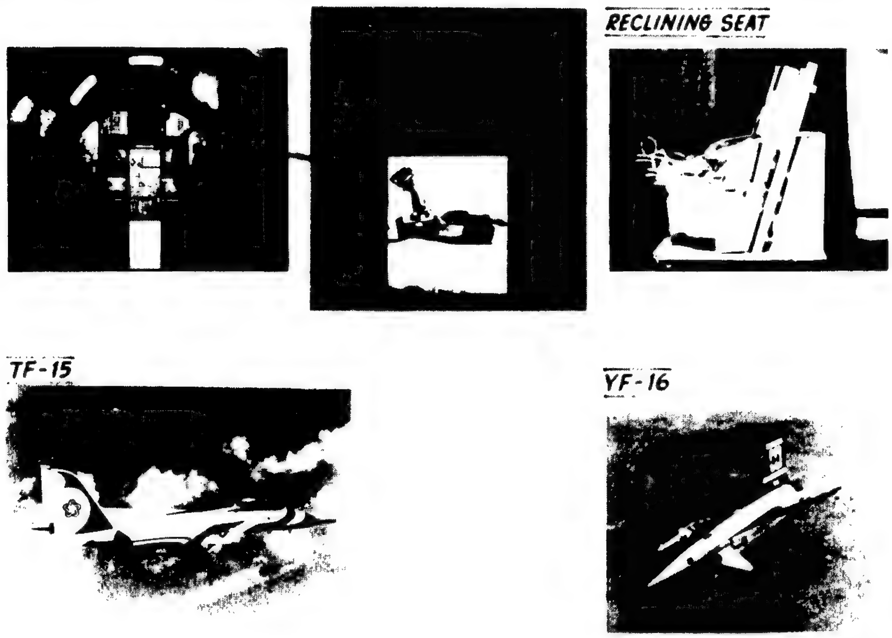
Crew Stations

The Flight Dynamics Laboratory and its predecessors have always led the field in human factors engineering -- the design of cockpits, seats and other components used by the crew, taking into account the abilities and limitations of the human body. During the fifties the Wright Air Development Center made advances in personnel seating and restraint systems, and in crew station configurations and equipment arrangements. The emphasis was on aerospace applications, which of course involve conditions very different from those faced by conventional aircraft. Strength, durability and ease of operation were improved both for restraints and seats. For example, seats capable of withstanding 16G acceleration were developed for the C-130, KC-135, C-135A and C-141. Troop seats large enough to accommodate fully equipped paratroopers or assault troops were designed for the C-130 and the C-141.

In the early sixties the Branch emphasized seating concepts for manned spacecraft and hypersonic vehicles. Crew fatigue and load attenuation under prolonged high-G acceleration were the prime considerations. A light-weight net seating system, consisting of a raschel knit cloth supported by a contoured frame, is now used for some pilot seats in supersonic and hypersonic craft, and was adopted for the Apollo capsule in the early sixties.

In addition to structural improvements, advances were also made in testing and prediction techniques for seats and restraints. Since crash conditions for aerospace vehicles are difficult to simulate, the Lab had to invent a whole new range of test facilities. By 1966 plans were under way for a Support and Restraint

HIGH ACCELERATION COCKPIT DEMONSTRATOR



- **COMPONENT INTEGRATION TO PERMIT AN OPERATIONAL EVALUATION AND DETERMINE SYSTEM LIMITATIONS**

Crew stations must be designed to protect the pilot against the high accelerations and forces experienced by modern fighter aircraft.

In 1966 a new system to test improved crew restraints was under evaluation.

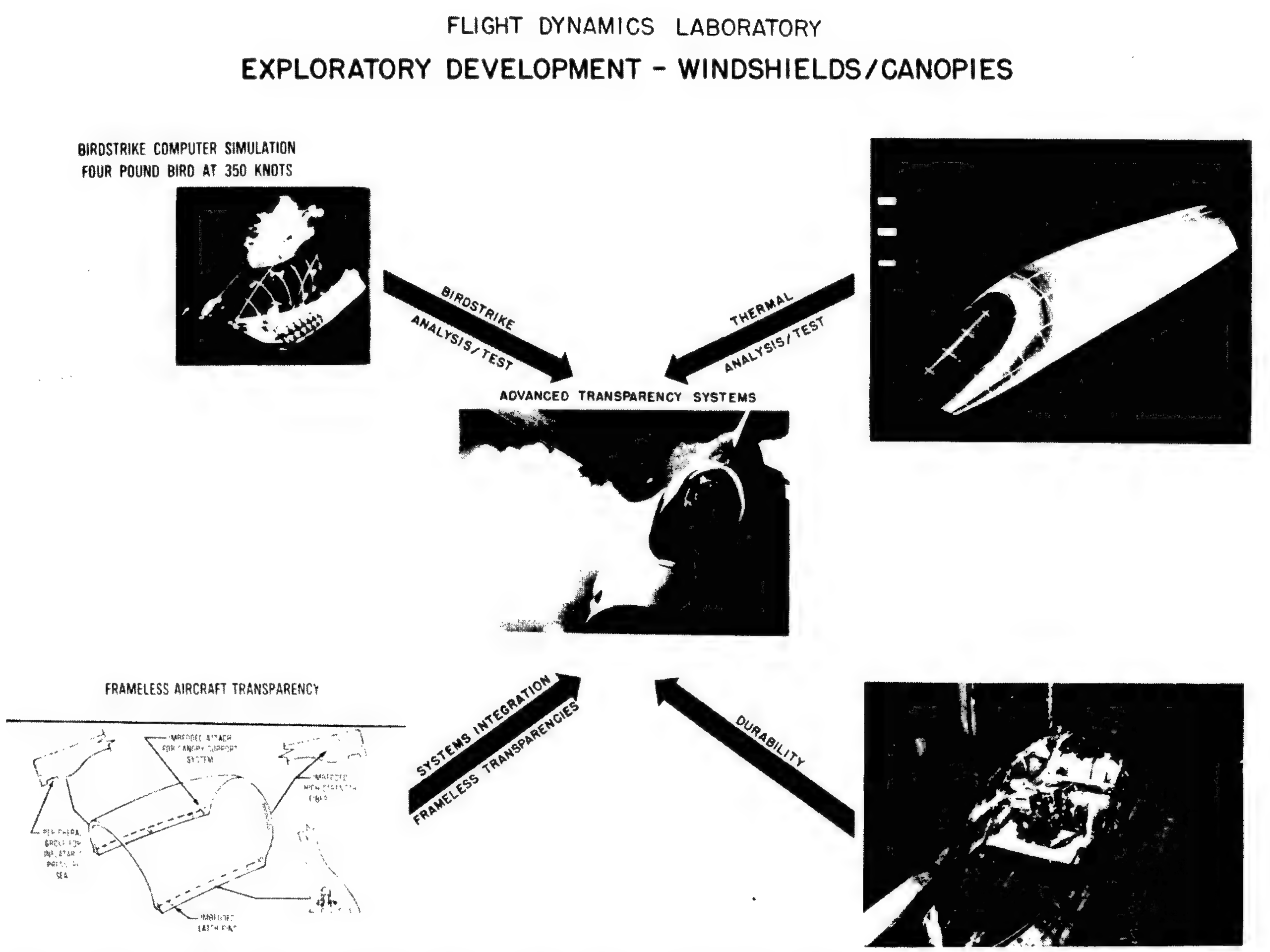
System Variable Acceleration Evaluator (SURVAE), to be used by the armed forces, FAA, and NASA.

New aircraft always require new concepts in crew station configurations, since instrument panels and controls are situated differently. The Lab rewrote the design requirements and control drawings for AFSC Manual 80-1, "Handbook of Instructions for Aircraft Design." The new data were used in the development of the Century series fighters, the B-52, B-57 and B-58 aircraft. After 1960 similar work was completed for the design of manned spacecraft. Previously unknown factors, such as weightlessness, extended confinement in small spaces, and air-sealed cabins had to be taken into account. Results were applied to the aerospace plane program. Beginning in 1964, the crew station team also worked on design factors for V/STOL fighters and transports.

Transparencies

In the late 1960s the typical mission profile of Air Force aircraft changed from high altitude, high speed to one of low altitude, high speed. The development of more effective radar and surface-to-air missile systems required this change, which gave rise to a new and significant operational hazard: bird impact on aircraft transparencies or windows. In the early seventies the Laboratory attempted to address this bird impact problem by applying existing technologies to the design of improved windshields. Since that time, the Lab has participated in the development of successful bird impact-resistant windshield and canopy systems for a number of aircraft, including the A/T-37, A-10, F-111, F-16, F-4, T-38, B-1, and A-7. The design methods used relied heavily on full scale bird impact testing to develop and qualify new systems. This approach proved time-consuming and very expensive.

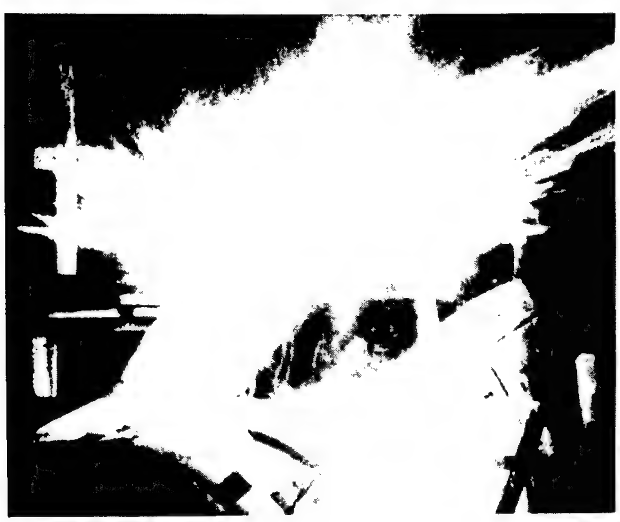
To reduce the level of full scale bird impact testing required in the development process, the Lab formed an office in the late seventies to develop computer analysis methods for simulating the dynamic structural response of transparencies to bird impact. By the end of the decade the MAGNA (Materially and Geometrically Nonlinear Analysis) computer program had been completed and delivered to the Air Force. Work in the area of transparency technology continued into the late 1980s with increasingly expanded missions. Additional



Advanced transparency systems must withstand birdstrikes and high temperatures, and must be integrated into existing systems.

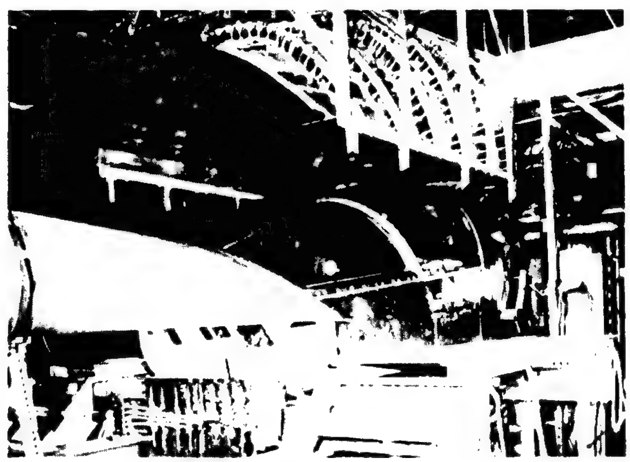
New transparencies like the one on the left provide better impact resistance and higher visibility.

Many pilots have lost their lives due to birdstrike penetration of the canopy.



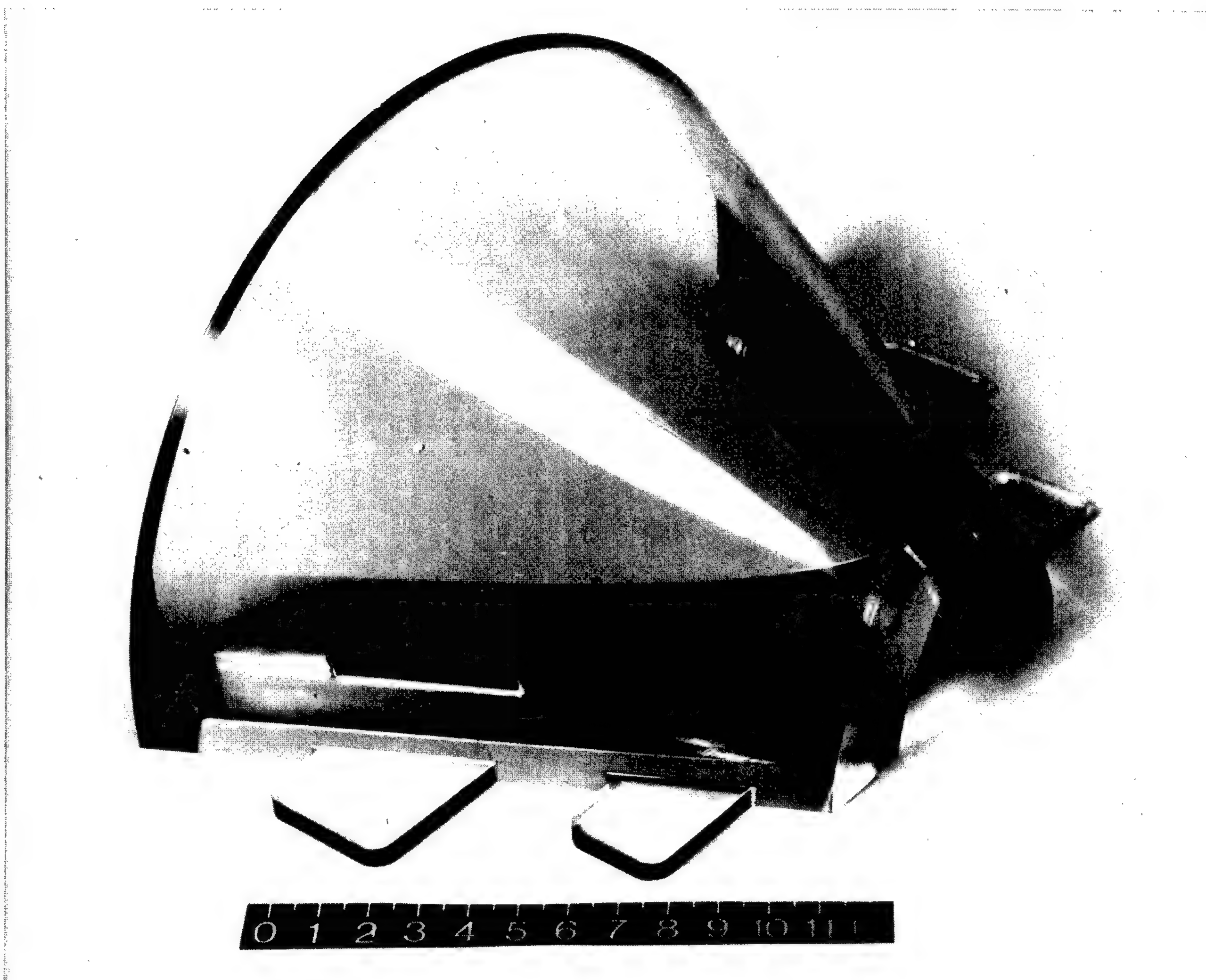
F-4 undergoing a birdstrike simulation test.

computer assessment tools were explored for aerothermodynamic applications in high speed aircraft, and for optical performance of transparency systems. Computer aided design and laboratory test methods came out of this pioneering work -- a growing suite of analysis and experimental tools which have been used to explore revolutionary transparency design concepts such as injection-molded frameless transparencies, fluid filled transparencies, and hybrid composite frame materials. Research emphasizes operationally acceptable and logistically affordable transparencies, integrating birdstrike resistance, durability, and optical quality. An R&D investment of about $20 million has saved more than $500 million in transparency costs since the mid-seventies.



F-111 transparency undergoing durability test. The canopy is subjected to realistic flight environments.

As requirements for future systems become more numerous and complex, the Lab has recognized a need for a concentrated effort to develop methods permitting trade-off of conflicting transparency system technologies to meet the requirements of advanced aircraft. The Mission Integrated Transparency System (MITS) program is exploring designs aimed at meeting future requirements for higher temperatures, longer life, more severe mechanical loads, and a host of natural environmental and advanced



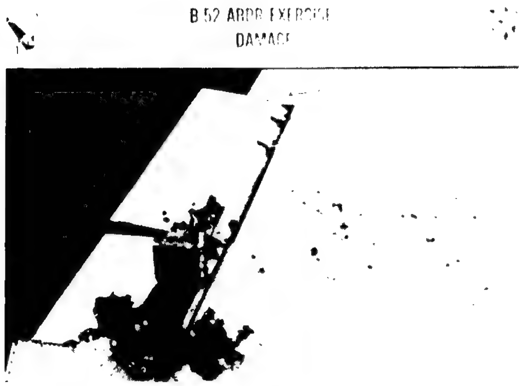
Once the injection molded transparency concept is fully proved, it should save considerable time and money.

wartime threats. As the lessons of integrated design are learned from the MITS program, they will be applied to future improved systems for retrofit to the existing fleet, as well as for new systems under development.

Survivability and Vulnerability

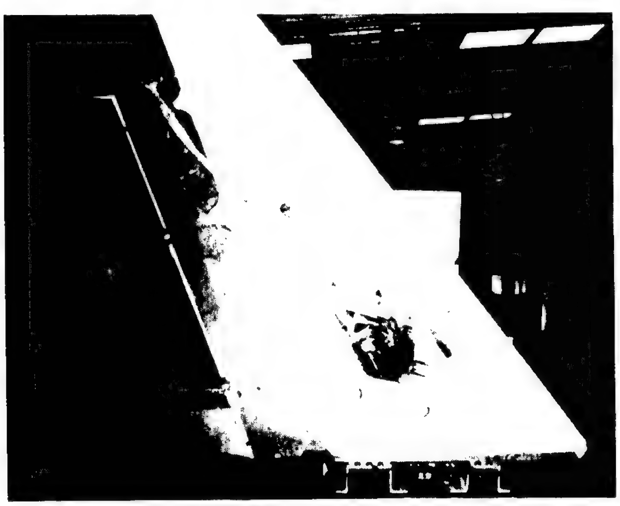
In 1965 an Air Force Systems Command task force headed by General Gilbert visited Southeast Asia to determine the reasons for the high attrition rate of combat aircraft in the region. Several vulnerability problems were identified and the task force recommended establishment of a special group in the Structures Division to examine the situation. The Vulnerability Group was quickly overwhelmed by the magnitude of the task and was therefore upgraded to the Flight Vehicle Protection Branch, in order to secure more funding and manpower. During its first years the Branch acquired a vast amount of research data from its Battle Damage Assessment and Reporting Teams in Southeast Asia, and established the Combat Data Information Center (CDIC). Today the Survivability Enhancement Branch carries on this work, particularly in the areas of armor and electrical hazards.

In the early seventies special emphasis was placed on passive defense in the form of crew station protective armor. New armor materials were investigated in order to improve crew

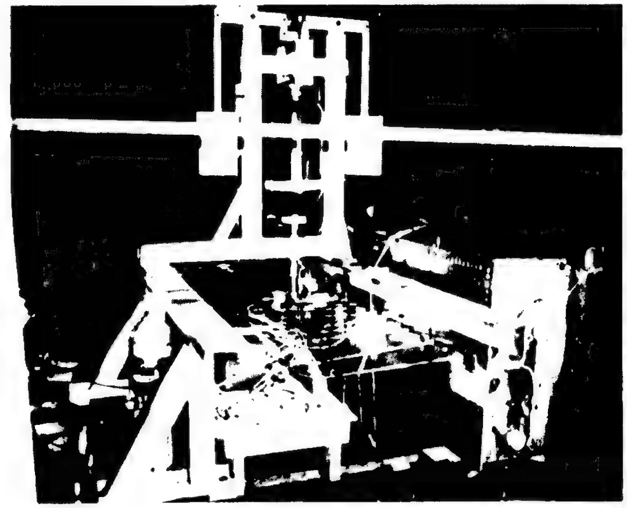


B-52 wing showing simulated battle damage.

The Lab is studying rapid temporary repair techniques for battle-damaged aircraft, to permit them to fly back to depots for permanent repair.

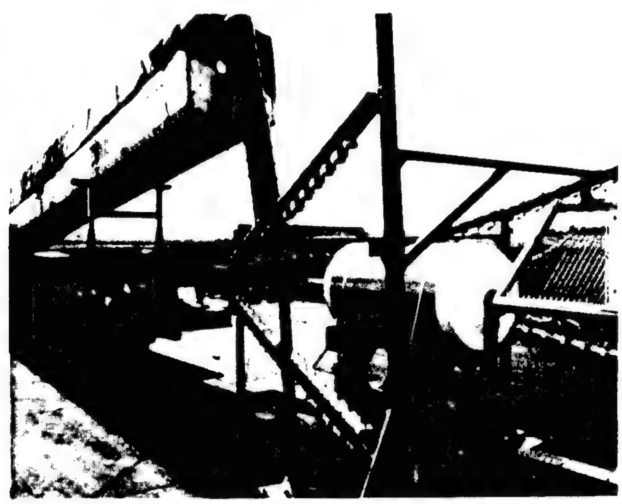


This A-7 composite outer wing panel was shot with a live round of ammunition to simulate realistic battle damage.



Test setup for the Halon Fire Protection Program.

protection without undue weight penalties. In 1975 the Survivability Branch produced a battle damage repair manual for the A-10, making extensive use for the first time of data collected by the Battle Damage Assessment and Reporting Teams in Southeast Asia. This work led to the establishment of the Aircraft Battle Damage Repair (ABDR) program in 1979. Considerable advances have been made in the capability for quick repair of battle-damaged aircraft, including all systems and subsystems. Today, the Division's goal is to bring ABDR capability for



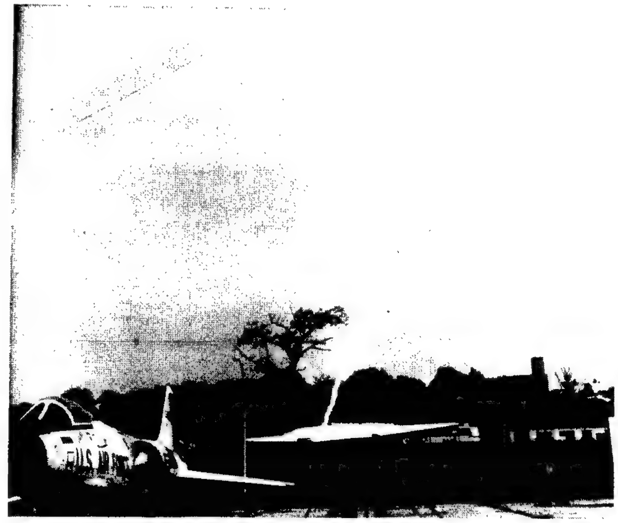
Components of the fast rise time generator used in the Lightning/NEMP measurement program.

new aircraft to the same level as that of current front-line weapon systems, and to improve overall ABDR capability by at least 50%. Projects include evaluation and expansion of the current data base and the development of advanced repair techniques and materials. Testing will continue on full-scale aircraft under simulated battle conditions. In particular, Division engineers hope to improve the ability to quickly define, assess and predict battle damage, in order to speed up repair times and increase combat sortie rate generation (that is, the rapidity and frequency with which combat aircraft can get into the air).

Studies were also conducted on better integration of controls and equipment with the crew's capabilities; the Branch experimented with various crew station arrangements, external vision techniques and personnel seating and restraint.

The Prototype Division was originally assigned responsibility for fire extinguishing technology, but it has been in Vehicle Subsystems since 1972. In 1980, the Lab conducted a unique experimental program to evaluate fire extinguishing systems to prevent fires in aircraft compartments due to ballistic impacts. Breaks in the aircraft skin can produce airflow 'drafts' which will adversely affect extinguisher performance. Existing techniques for measuring airflow across cavities were adapted, and a data base was acquired. Two types of fire extinguishing systems were tested, one utilizing bottles and the other a high rate discharge concept. Both were successful. This program, together with an investigation of the Halon 1301 extinguisher conducted by the F-16 SPO, established criteria for the design of fire extinguisher systems in many aircraft.

The electrical systems of aircraft have always been adversely affected by lightning encountered during flight missions in bad weather. In 1977 the Vehicle Equipment Division completed an electromagnetic coupling model for the prediction of lightning-induced electrical transients (brief pulses or surges) on internal

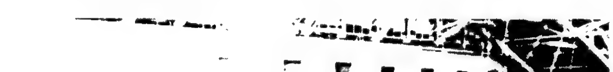


F-15 wing being studied for effects of a simulated lightning strike.

wiring. Experimental tests conducted over a three-year period in the Aircraft/Atmospheric Electricity Coupling Model program provided a data base, and a Learjet equipped with skin sensors flew several test missions.

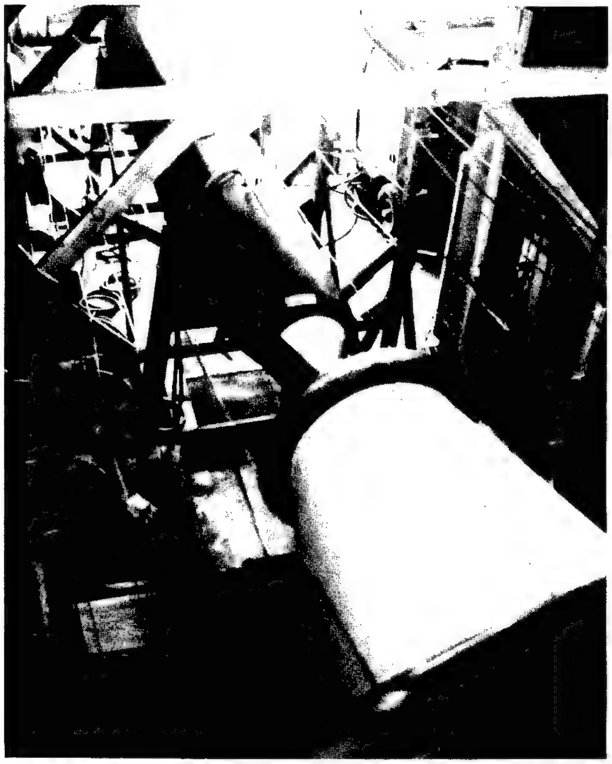
Rocket-Triggered Lightning Investigation test atop Mt. Baldy, New Mexico.

F-16 surrounded by equipment to test and record a 30-kiloampere, full threat level simulated lightning strike, and its effects on the flight control system.



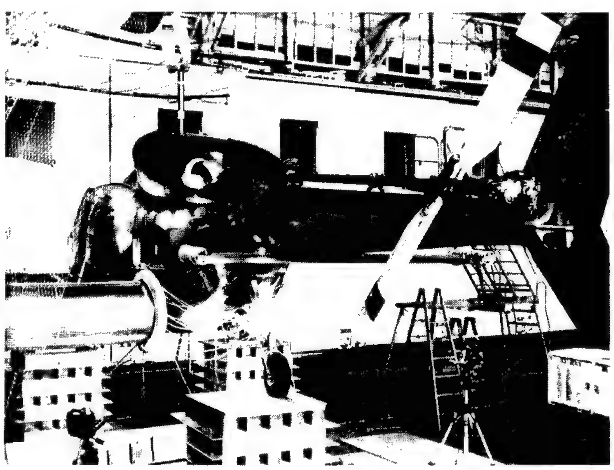
The generator used to conduct AEHP tests is located at Patterson Field.

The Atmospheric Electricity Hazards Protection (AEHP) Advanced Development Program began in April 1982 under contract with Boeing. The program was aimed at improving protection from electrical transients in aircraft wiring induced by lightning and static charges. In Phase 1, a variety of electronic and avionic equipment was tested for reaction to lightning strikes, and several protection schemes were defined. Phase 2 tested these concepts in a modified F-14A and an Army all-composite helicopter. When the program closed out in May 1988, a report was published offering design criteria for incorporating AEHP into existing and future aircraft.

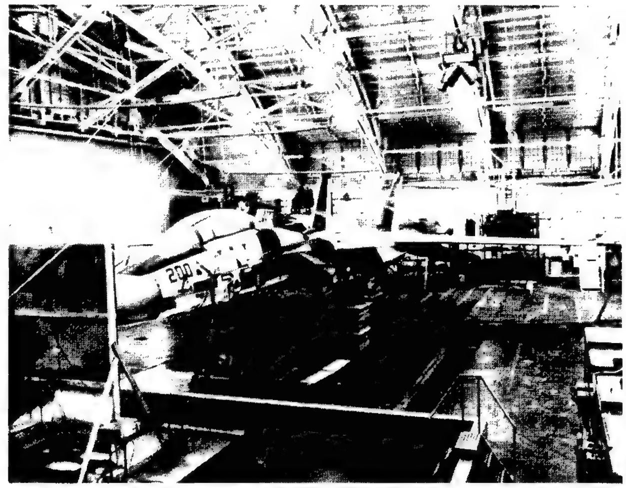


The Atmospheric Electricity Hazards Simulation Facility tests an air launch cruise missle.

Since aircraft first began to use electrical control devices and radios, electromagnetic pulses -- commonly in the form of lightning -- have been a recognized threat to mission and safety. Today's aircraft, which incorporate



Electromagnetic discharge test on a composite body helicopter test bed.



Composite wing section of an F-14, tested under the Atmospheric Electricity Hazards Protection (AEHP) program

advanced composite materials and avionics with low voltage, fast transient integrated circuits, are particularly susceptible to this problem. In 1984 the Survivability Enhancement Branch conducted flight tests with a specially equipped FAA C-580 aircraft near and inside Florida thunderstorms to measure the effects of lightning strikes. Ground tests were also conducted with a non-nuclear electromagnetic pulse simulator. The program provided a data base for further research on lightning and NEMP protection.

The FDL/FAA Lightning/NEMP measurement program tests a Convair 580 with a mobile lightning simulator.

Unusual "sailwing" parachute demonstrated at Wright Field in 1966, for possible use in precision delivery of supplies and equipment to combat troops.

Aerodynamic decelerators

Parachutes and other deceleration devices are used not only in crew escape systems, but also have a wide application for many types of weapon delivery and in space vehicles. Some high-speed aircraft use parachutes to accomplish short-runway landings. Before the Lab took over parachute experimentation in the early fifties, very little research had been done anywhere. Trial and error was the usual method of testing, and parachutes could be used only in limited circumstances. Today, thanks in large part to work done at the Flight Dynamics Lab, the dynamics of deceleration are thoroughly understood, and reliable prediction techniques exist. Parachutes and similar devices can be used under almost any operating conditions, and for a variety of purposes undreamed of forty years ago. Well over one hundred weapon systems use decelerators developed at FDL, as do many Army, Navy and NASA craft.

In 1951 only one type of parachute was available for dropping personnel and equipment from aircraft. This was the familiar circular cloth chute, type C-9. One of the Lab's earliest improvements was the T-10 (1952), the extended skirt chute used by paratroopers. The introduction of supersonic jet aircraft led to another advance, the highly stable guide-surface C-10 chute. Dummies equipped with recording devices were developed to facilitate parachute

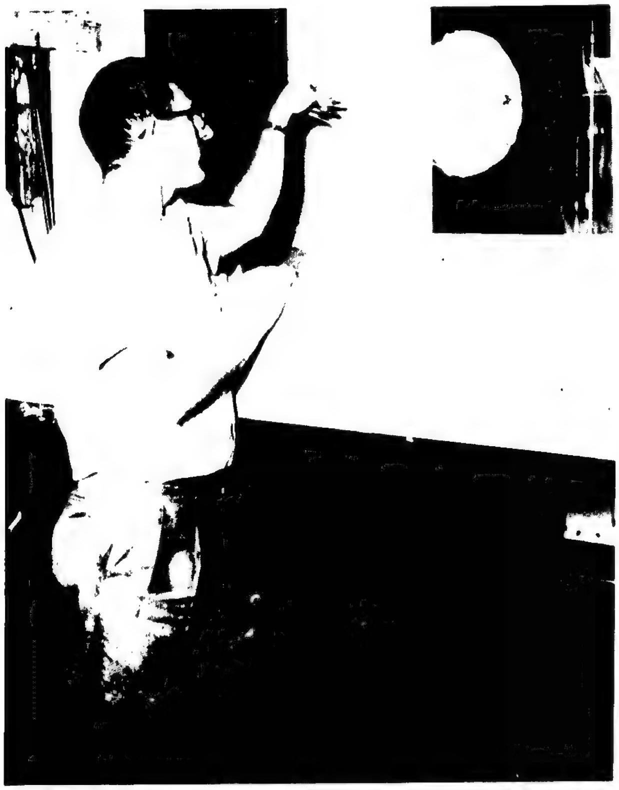
A-26 conducting a flight test of a drag chute design.

testing. Perhaps most important of all, the automatic-opening parachute (type C-11) was introduced in 1954. This chute, which became universally standard, will open even if the wearer is unconscious.

Advances in equipment parachutes emphasized heavier payloads. During the fifties the development of clustering techniques increased payload from approximately fifteen thousand to forty thousand pounds. In 1964 a new fast-opening chute was introduced which permitted dropping of heavy loads from cargo aircraft at low altitudes. Nearly all varieties of drop and escape chutes now used by the US armed forces originated at FDL.

Starting in the late 1950s and continuing into the early seventies, the Lab undertook a commitment to improve the performance of decelerators for high speed applications including supersonic and hypersonic environments. The ribbon parachute was replaced by a more efficient ring-slot parachute for aircraft deceleration. In the mid to late sixties, the Hyperflo, the Supersonic-X, the ram-air inflated balloon ("ballute"), and the widely used Hemisflo ribbon parachute were made available by the Equipment Division. Deceleration systems to control the re-entry and recovery of early unmanned space vehicles were also, in large part, products of FDL.

In the early 1960s the Lab began to explore the possibilities of controlling and enhancing the natural gliding tendencies of parachutes. The design of 'chutes for this capability evolved from



An engineer adjusts the guy lines of a parachute in the test section of the Air Blower in Building 255.

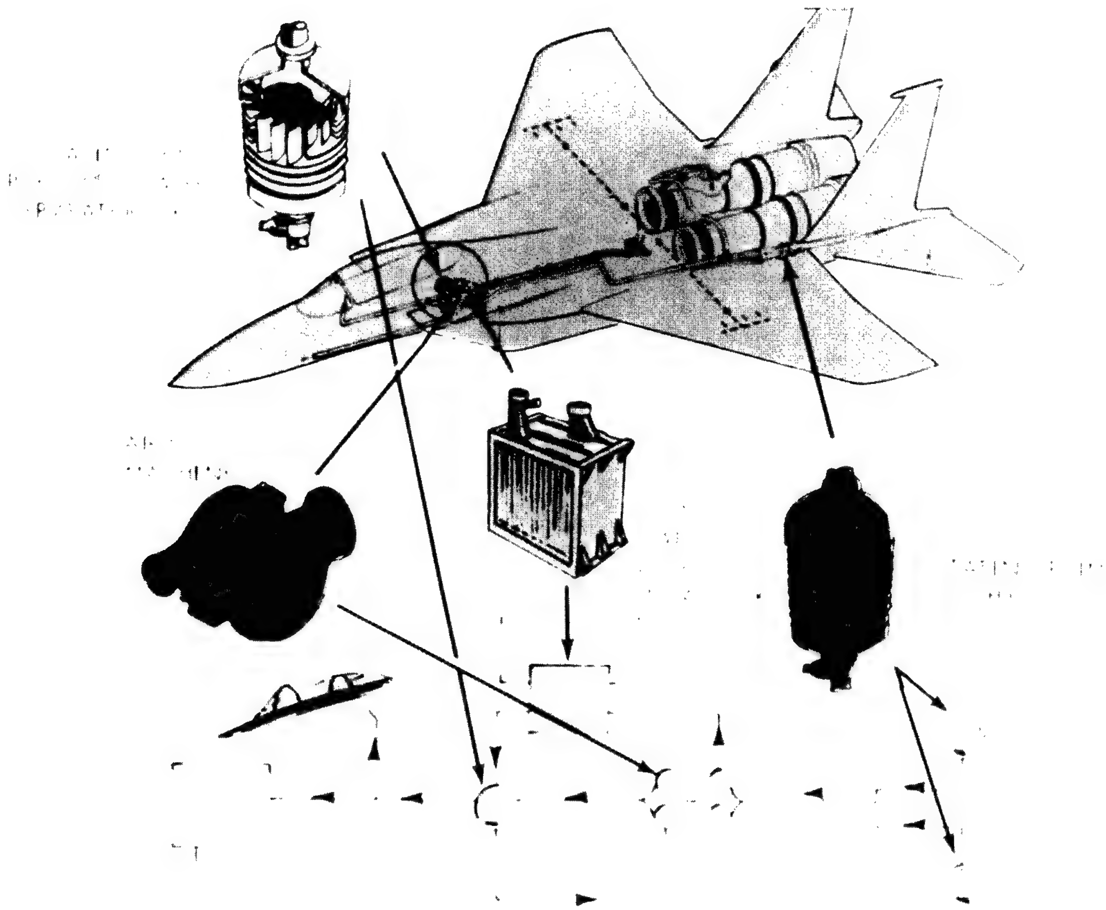
round parachutes with a controllable opening, to rectangular parachutes which looked more like an airplane wing. By the early seventies the gliding capability of these parachutes provided a horizontal velocity of three to four times the vertical velocity. This ability to travel toward an impact point which was three to four times further than the deployment altitude resulted in successful demonstration of radio-controlled automatic homing systems for delivery of cargo packages weighing up to two thousand pounds. In the late 1960s and again in the seventies the Division explored integration of these parachutes with propulsion systems for use as part of a self-contained flying ejection seat for aircrew rescue.

The Lab helped resolve problems associated with the need to pack more parachute system into less volume. Early efforts yielded techniques for packing parachutes of up to 100 feet diameter to densities greater than that of oak. Successful deployment from such high-density packing was addressed through development of deployment control technologies and ground based deployment testing techniques using high speed photography. These packing technologies were employed to develop solutions for problems with the F-111 crew escape module recovery system, spacecraft recovery systems, and RPV recovery systems designed for mid-air retrieval. The continuing need to pack more parachute into less volume led to exploration of the DuPont Kevlar fiber which, because of its high strength-to-weight ratio, offered a reduction of about 50% in basic material volume over that of conventional nylon. Laboratory development of Kevlar parachute materials and subsequent quantification of design criteria for using these materials met many of the needs of high-density packing.

Environmental Control

During 1951-1959 the Lab explored a variety of problems in what was then called "aircraft conditioning." Basic heat transfer research on fuselage, wing and transparencies was supplemented by studies of visibility, ice prevention and removal, and air conditioning. In order to do the most thorough job possible, researchers went back to the basics, conducting experiments on the properties of air and water vapor, thermal properties of aircraft materials, and heat transfer with variable surface temperature distribution.

By the end of the decade this basic research was beginning to demonstrate practical applications. For example, the operation of high speed jet aircraft in rainy conditions poses special problems. The Lab improved the jet air blast method of rain removal, and the new system was used on most supersonic aircraft, including the F-100, F-105, KC-135, C-133 RB-66, B-58, C-141, F-4C, and F-111. New techniques were developed for simulating rain in wind tunnels; and on a theoretical level, researchers defined the laws governing fragmentation of water droplets under high pressure airstreams. The Lab also

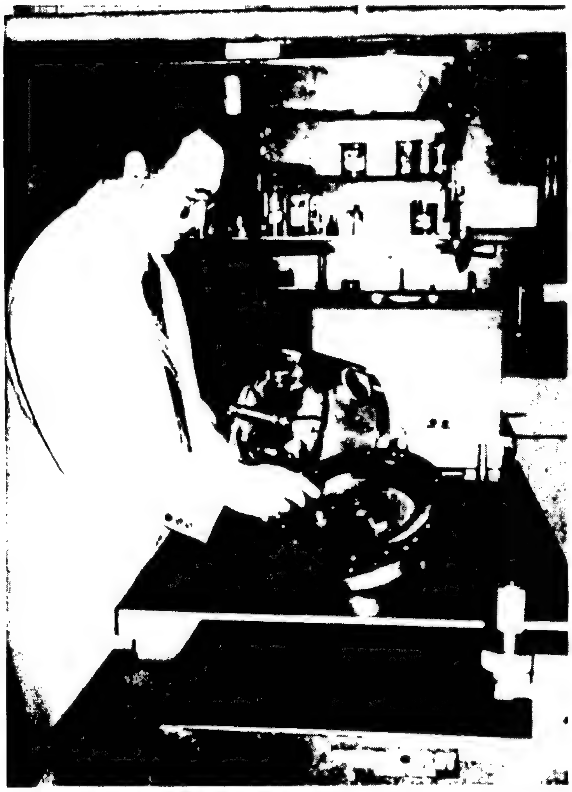


All aircraft carry some form of environmental control. These systems supply clean air for the crew, cooling for electrical equipment, and many other functions.

developed laminated glass windshields with electrically conductive coatings for prevention of ice, frost and fog. Such windshields are now used in almost all aircraft. Infrared heating for the same purpose was also explored, but proved unfeasible.

Wind tunnel studies were conducted on the problem of ice formation on the airframe, and bleed-air anti-icing systems were developed for jet aircraft, utilizing high temperature air from the engine compressor. Cyclic electrothermal de-icers were also designed, and these studies led to a significant Design Manual that demonstrated methods for calculating pressure drop in ducts, water impingement on airfoils, and coefficients of heat and mass transfer by convection in airfoils. The de-icing of radomes presented special difficulties which were also solved by Lab scientists. For missiles and certain special-purpose aircraft which require de-icing for only very brief time spans, other options were explored. Conventional thermal anti-icing systems were greatly simplified, and various methods of external air blasting over airfoil surfaces were devised.

The air conditioning requirements of aircraft cabins grow more complex as the range and speed of modern vehicles increase. Thermodynamic studies conducted throughout the 1950s allowed more accurate prediction and more efficient system designs. Air cycle refrigeration units were improved, with attention given to such details as the long-term effects of vibration and the effect of ram air circuit drag penalties on heat exchangers. Vapor air cycling units were developed for the B-70. A great variety of air filters were fabricated and tested, and a remote control cabin pressure regulator



Engineer inspecting an aircraft environmental control system built by a contractor.

A test conducted on a Propulsion Lab test stand explored propeller de-icing concepts.

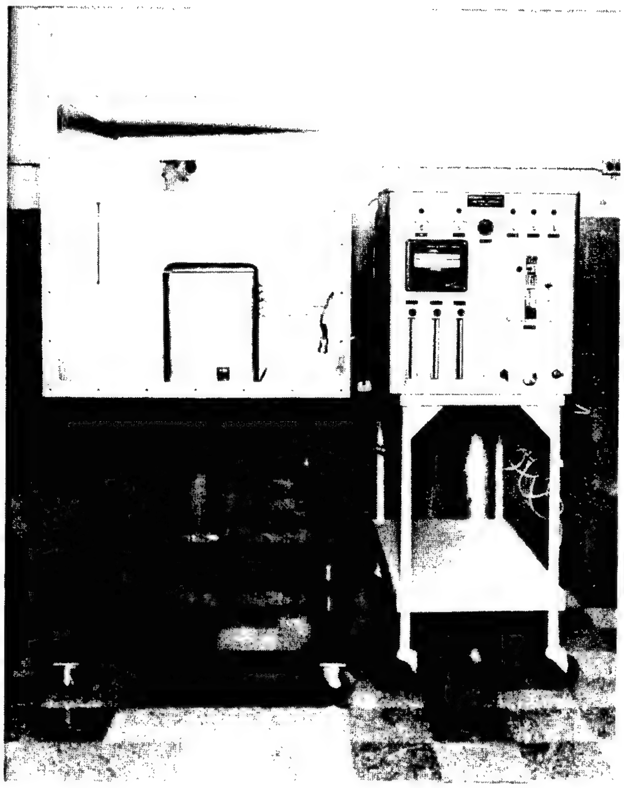
system was designed. In the late fifties, special attention was given to conditioning for manned spacecraft. TR WADC 55-353, "Artificial Cabin Atmospheres for High Altitude Aircraft," became the definitive foundation for later advances in this area.

An in-house effort during the early seventies created the closed-loop Environmental Control System (ECS) concept. Industry studies confirmed the Lab's estimate that up to 6% savings could be realized in gross take-off weight of tactical fighters like the F-15. Air and vapor thermodynamic refrigeration cycle components were developed, such as positive displacement compressors, rotating heat exchangers, fluidic environmental control systems and compact heat exchangers. This period of development expanded the technology base and set the stage for further development of closed-loop ECS in the 1980s.

A flight test program that validated the use of high pressure water separation in an advanced environmental control system was conducted between 1970 and 1977, using an F-15 as a test bed. The results showed that a 15% reduction in life cycle costs could be achieved by using the concepts tested. The high pressure water separation technology was applied to the F-18 and the Boeing 757 and 767.

Atmosphere Control

In 1959 the Lab commenced research on self-contained atmospheric systems for space vehicles. As in many other areas of aerospace research, it was necessary to start almost from scratch, but within four years projects had been completed on many aspects of atmosphere control. Approximately twenty technical reports were published, covering contamination control, regenerative type air purification systems, and maintenance of artificial atmospheres. After 1963 the Lab concentrated on regenerable atmosphere control systems, and this new technology was applied to MOLEFT, MORL, the



Project OSCAR chamber, a piece of test equipment in the Atmospheric Control Lab.

Apollo spacecraft, and similar projects. Conventional aircraft also benefitted. A self-contained oxygen system was developed, utilizing concentrated oxygen from ambient ram air.

One of the work areas associated with the old Atmospheric Control Lab in the basement of Building 45.

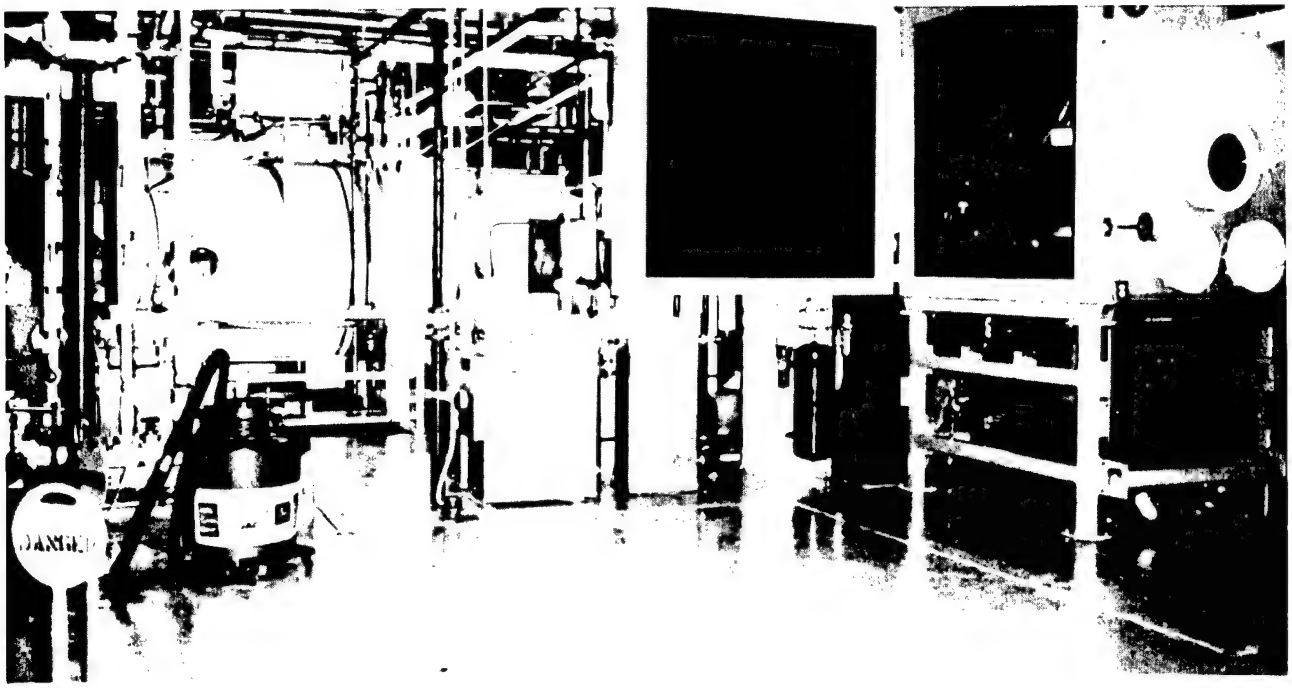
Thermal Control

During the period 1959-1964 the Lab developed thermal control systems for a variety of spacecraft designs. As in environmental control, the thermal problems of exo-atmospheric craft are quite unlike those of conventional aircraft. Heat must be dissipated by radiation, and the thermal system's design must be extremely accurate. Weight and volume penalties must be kept low and at the same time a very narrow range of temperatures must be maintained to ensure the survival of the crew. In addition, weightlessness creates a whole new range of problems involving heat transfer, fluid transfer and fluid orientation. Finally, the system must be integrated precisely with other systems. In this endeavor the Environmental Control Branch made its first extensive use of computers, reducing the number and cost of vacuum chamber experiments. Out of this research came twenty-six technical reports and nine computer programs which became the basis for all later military and civil thermal systems designs. The new technology was essential to the design of many satellite and weapon systems and for the Mercury, Gemini, and Apollo programs.

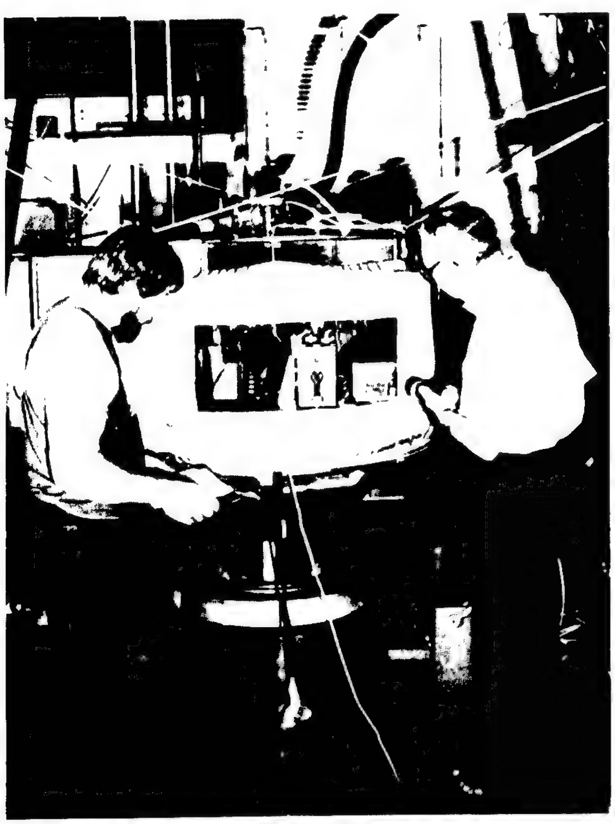
In the later 1960s the Lab turned to development of new thermal control systems for hypersonic aircraft. Supersonic vehicles such as the B-58, F-111 and B-70 carry a water supply as a heat sink; the water is vaporized and ventilated overboard. Because the weight penalties of such a system are too high for hypersonic aircraft, the Lab has begun searching for a radically new concept. Integral cabin wall heat exchangers and vapor compression cycles showed early promise.

Combined Environment Reliability Test

A high rate of environmental stress-related failures in avionics equipment encouraged the Equipment Division to develop new test methods for evaluating equipment. The Combined Environment Reliability Test (CERT), designed in the late sixties, was intended to create reliable



The Combined Environment Reliability Test (CERT) Facility tested effects of temperature, pressure, vibration, airflow and humidity on various pieces of avionics equipment.

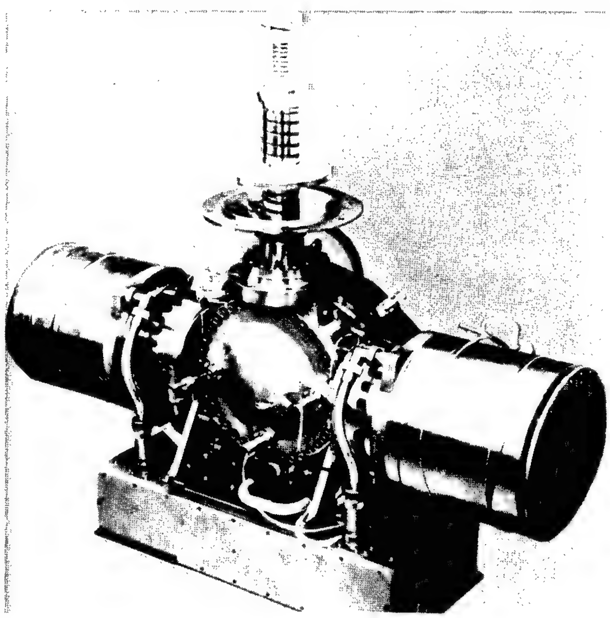


Technicians inspecting data from the CERT facility.

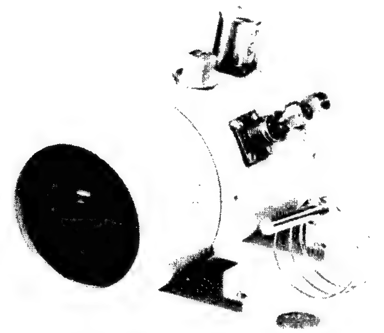
and accurate test conditions for a wide range of altitudes and temperatures. CERT was based on the concept that a one-to-one correlation existed between life and failure modes of electronic equipment in the field, and that these conditions could be reproduced in a test facility. An old altitude test chamber in Building 93 was converted under the guidance of Dr. Arnold Mayer and Kent Prather of the Environmental Control Branch. Rapid thermal and moisture transients (changes) were achieved while maintaining altitude simulation in the test chamber. Initial tests performed on various avionics items were so successful, and the results so surprising, that some experts questioned whether the data had been fabricated! FDL undertook an extensive test program to validate the CERT concept. After 24,500 test hours involving eighty different types of equipment, a four-to-one superiority for CERT over other test methods was proven. Although the cost of converting existing equipment would be high, both ASD and AFSC adopted CERT, and in its present form it is the established standard for industry and the military.

New Directions in Equipment Research

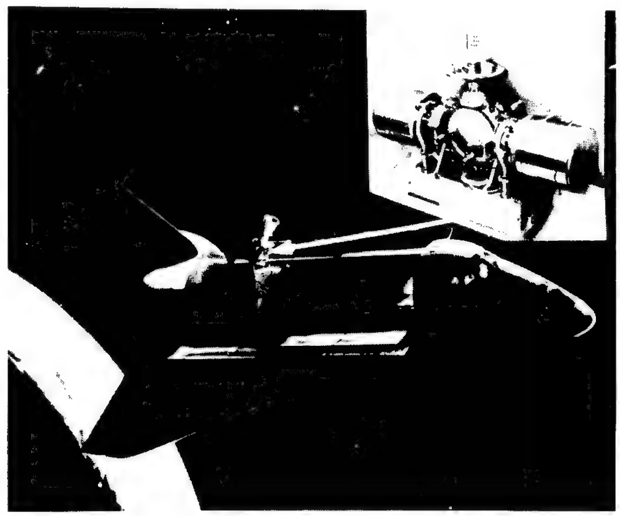
Changing technological requirements led to a reorganization of the Environmental Control Branch in 1973. The new Combined Environments Test Group was responsible for analyzing the dynamic environments of temperature, humidity, altitude and vibration under which aircraft equipment functions. Qualification test criteria were established and improved. The Advanced Oxygen Systems Group developed techniques for supplying, measuring and regulating the crew air supply. The Advanced Thermal Control Group in the early seventies was working on rotary-vaned air cycle machines, osmotically pumped heat pipes, and rotating heat exchangers. The Advanced Cryogenic Systems Group produced cooling systems for infrared detectors, lasers and reconnaissance devices and in 1974 was working on a cryogenic cooling system which could function for up to three years, unattended, in a spacecraft. In 1971 the Division initiated development of a cryogenic refrigerator for an infrared space telescope. This work led in 1978



Miniature Vuilleumier (VM) cryogenic cooler, designed to provide continuous long-term cooling in spacecraft systems.



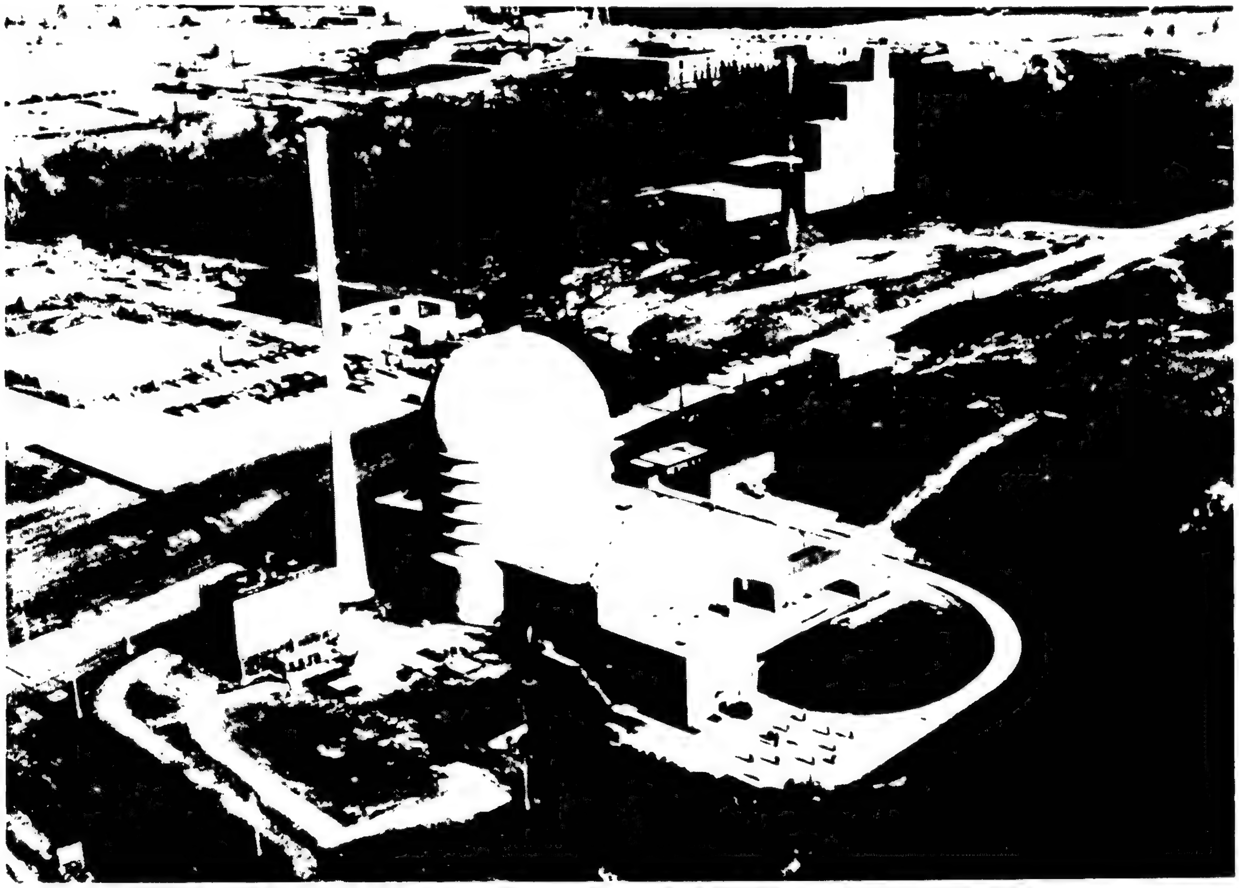
Standard Cryogenic Cooler, used to cool infrared detectors on aircraft and spacecraft.



Cryocoolers for space applications (1971).

to the five-year Spacecraft Vuilleumier Program, which evaluated twelve different components with the goal of extending the cooler's life to five years or more. The unique Tri-Ring Displacer Seal has now been tested for more than five years without a failure.

Cryogenic research has become increasingly critical in the past decade. In June 1976, for example, the AIM-9L Program Office requested FDL to develop a cooler for the AIM-9L missile. Fourteen months later the cooler had been designed, fabricated by Hughes Aircraft, and



The Air Force Nuclear Engineering Test Facility performed research in basic engineering, plant and reactor operations, and physics. The reactor was transferred to AFIT and later closed.

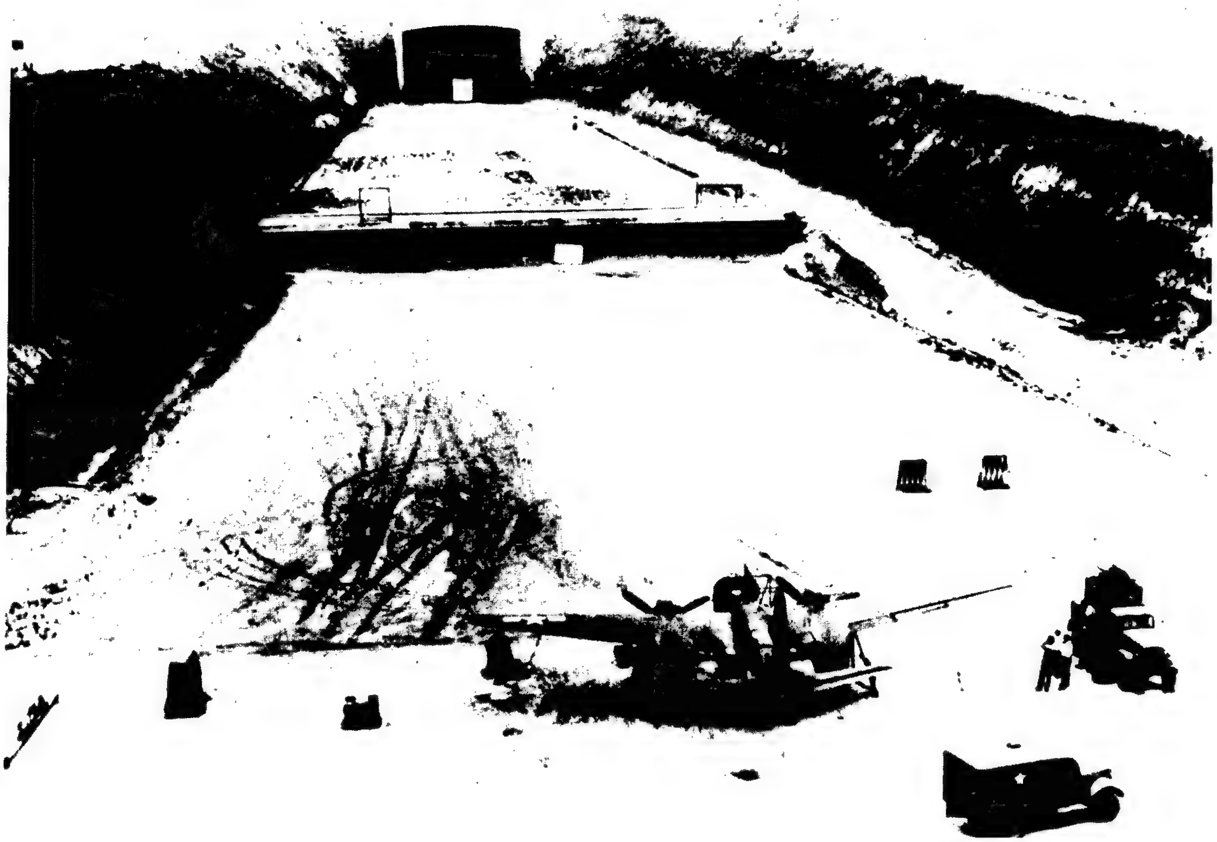
tested at the Naval Weapons Center in California. Microphonic problems caused failures in the configured aluminum bronze gears. The Lab modified the design and by October 1978, the program was successfully terminated. During 1979 the Navy tested about eighty missiles with the new cooler. During the same period the Lab developed the Air Force Standard Cryogenic Cooler, which was intended to replace a wide variety of coolers then in use.

In 1978 the Lab demonstrated that the Vuilleumier cycle could be adapted to small, lightweight, long-life coolers. The new standard cooler is a 2200-hour MTBF (mean time between failures) split VM device capable of retrofit into most airborne infrared systems. Under testing it survived environmental conditions well beyond those of any existing cooler, and flight testing will continue in the future.

Facilities

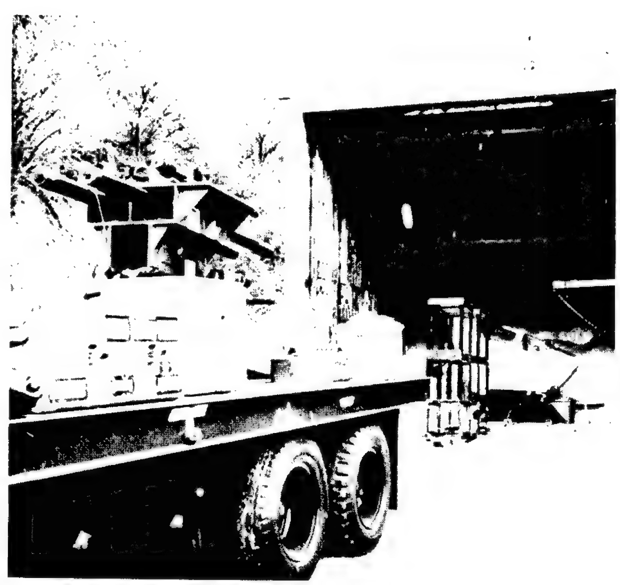
During the 1960s the Nuclear Facility Branch of the Vehicle Equipment Division operated the Air Force Nuclear Engineering Test Facility at WPAFB. The reactor, still a Wright Field landmark, generated ten million thermal watts and included a variety of irradiation facilities. After the completion of the demonstration program the facility was transferred to AFIT.

The Survivability Enhancement Branch operates the Aircraft Survivability Research Facility (ASRF), which studies potential threats from non-nuclear weapons. The facility includes three terminal ballistic test ranges, capable of simulating threats ranging from sidearms to 57mm HEI (high explosive incendiary) and exploding missile warhead fragments. Armor



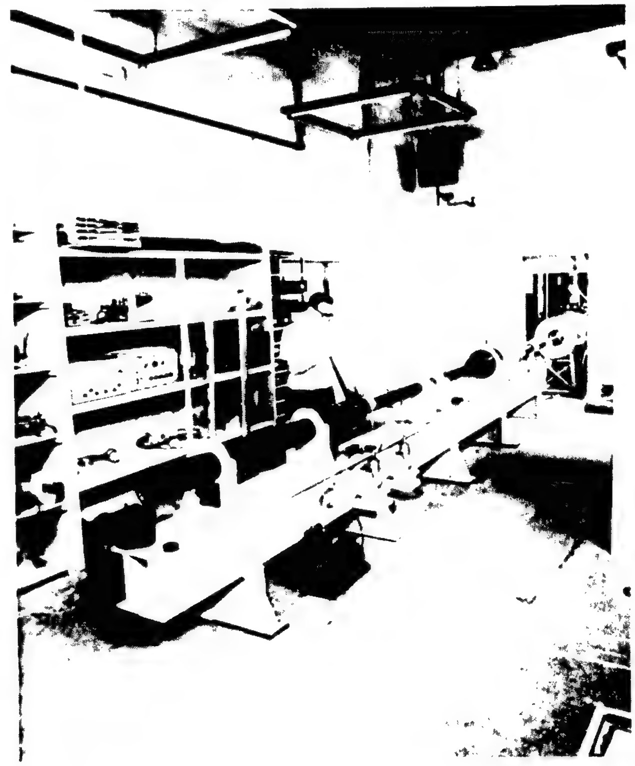
A-20 undergoing tests at a Wright Field gunnery range, shortly after World War II.

Tests have been known to get a little hot for the "Bang Gang" at ASRF, as jet fuel can ignite under certain conditions.



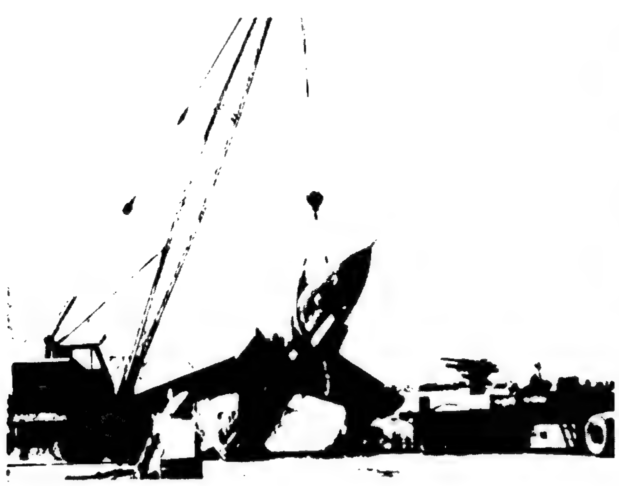
Mobile Threat System, set up in Range 2 to test ballistic impact characteristics of an F-111 transparency.

The Aircraft Survivability Research Facility (ASRF) includes 3 ranges, a control building, and a specimen preparation building.

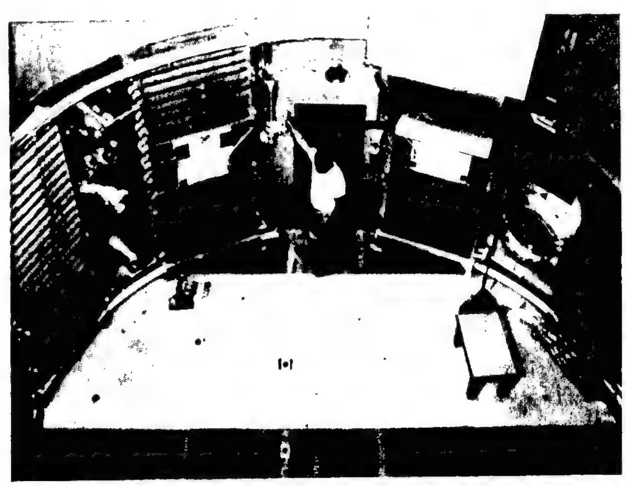


Technician working on a gas gun, used to determine impulse loads in flight vehicle structures.

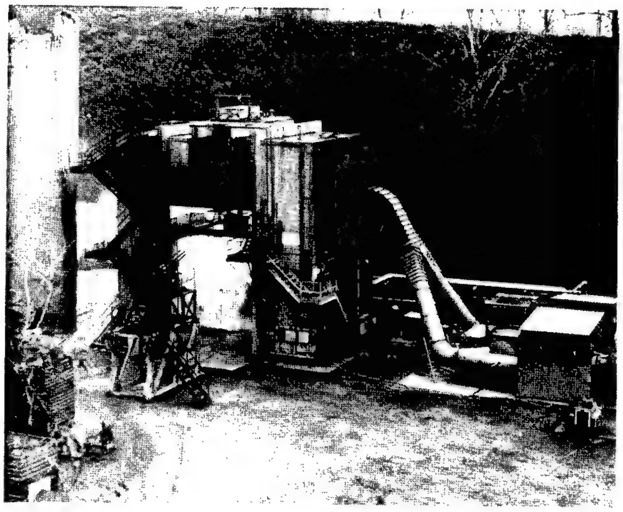
certification, hydrodynamic ram experiments, fuel cell inerting and ballistic tolerance tests are conducted at the ASRF. The unique Range No. 3 can test full-scale models under realistic airflows, utilizing actual explosive projectiles and simulating emergency escape procedures. ASRF can also simulate a wide spectrum of mechanical and aerodynamic loads.



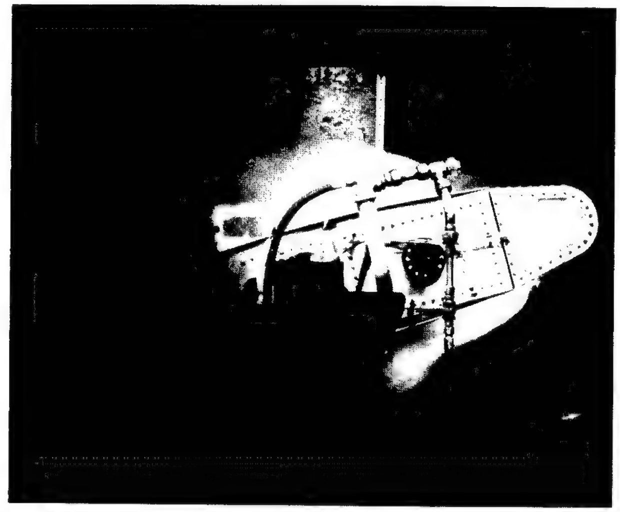
Mobile Threat System, set up at a remote location to conduct survivability tests on an F-105 aircraft.



Engineer inspecting the Systems Altitude Facility in Building 22.

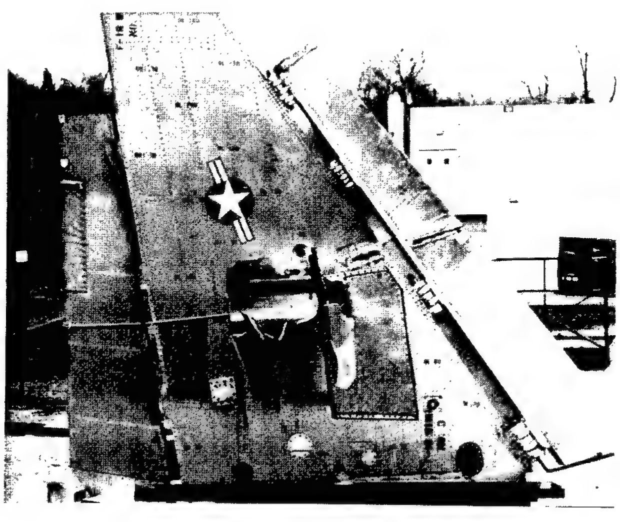


Range 3 blows engine bypass air over fueled and loaded aircraft parts for realistic survivability testing.

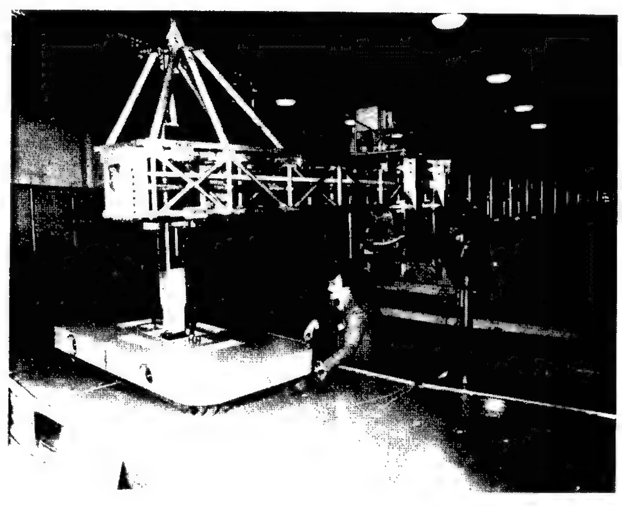


This fueled wing section has been ballistically impacted. Note the fuel streaming out of the wing box as airflow passes around it.

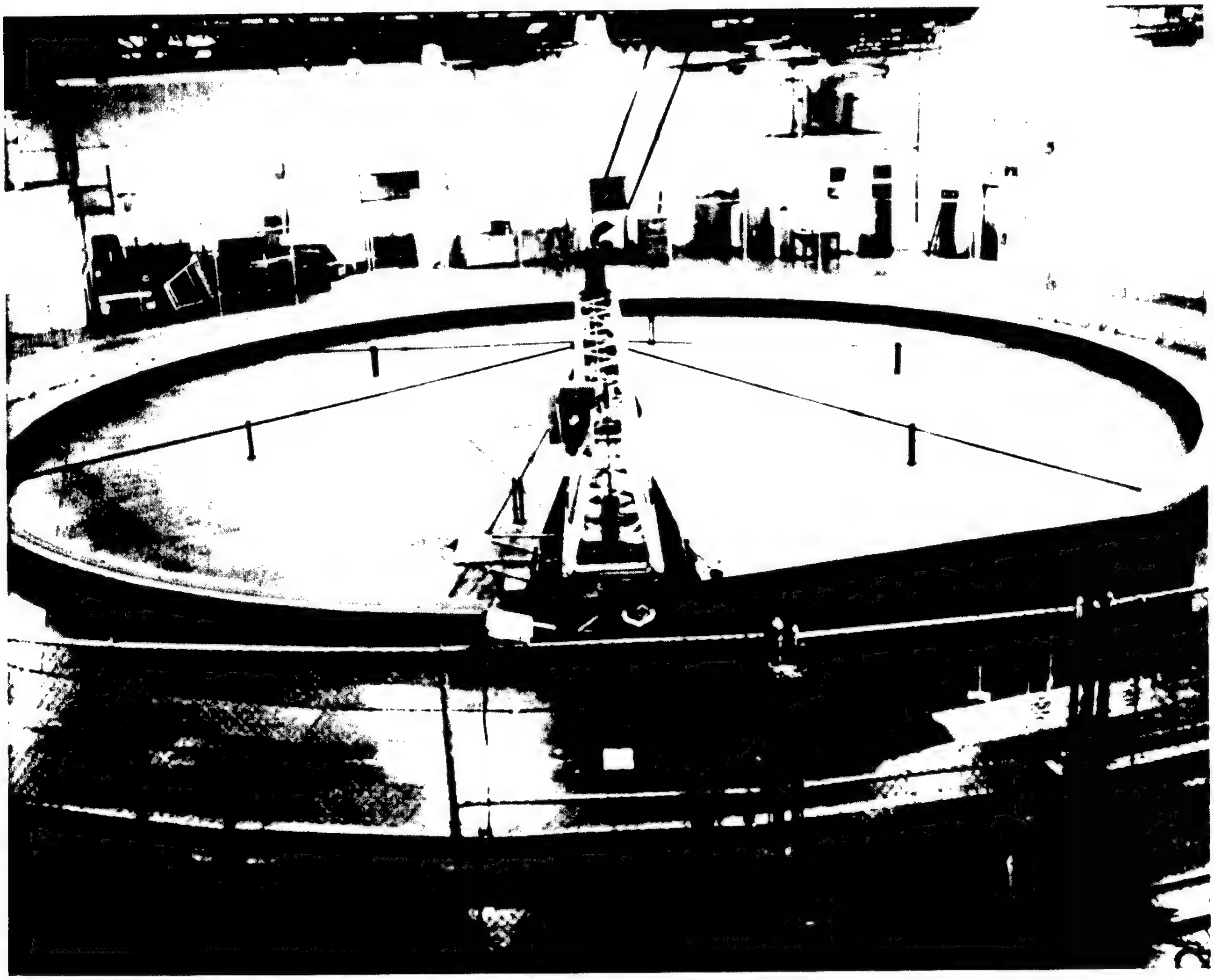
The Division also presently uses an automated aircraft tire/wheel/brake dynamometer capable of simulating nearly the entire ground operation spectrum. A Tire Flat Surface Test Machine provides a unique capability to establish tire mechanical properties and ground handling characteristics under loads of up to 80,000 pounds at yaw angles up to 20 degrees and/or camber angles of up to ten degrees. A Vertical Ground Loads Test Machine can test a complete landing gear under vertical loading conditions. In its shock mode, a 100,000 pound dead weight and a 120,000 pound impulse weight can be applied through the equipment table. In the vibratory mode, a 35,000 pound article can be tested.



This F-16 shows what can happen when an aircraft is impacted with a ballistic round. Survivability engineers test such wings to see if they can get the pilot home.



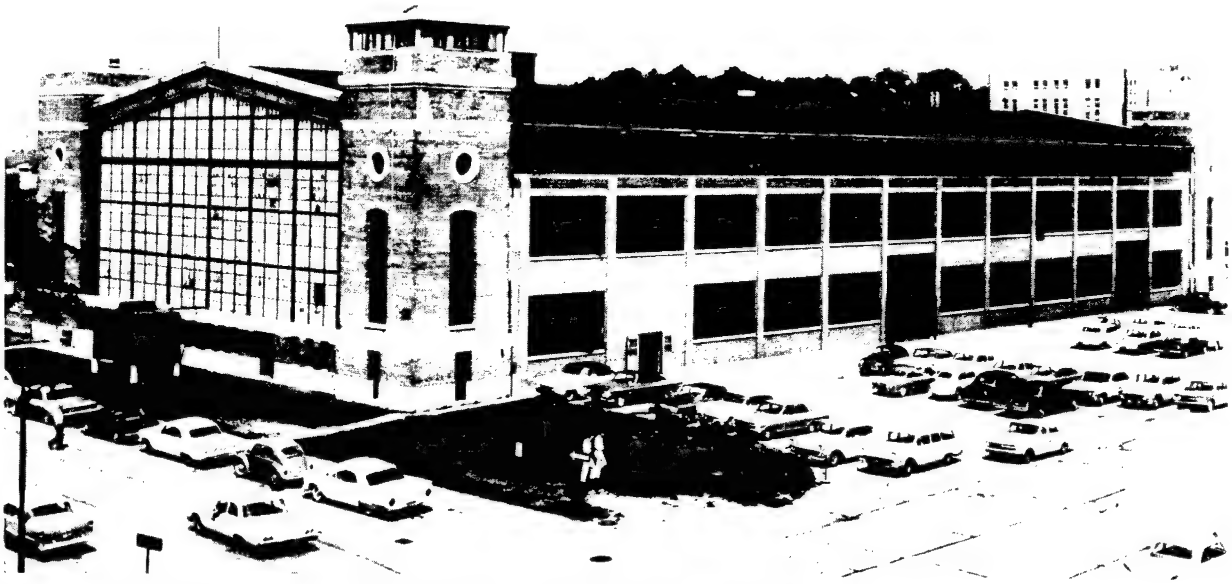
Engineer inspecting an air cushion test article mounted on the Mobility Test Facility. Note the rubber skirt and the fan inlets on the scaled equipment transporter.



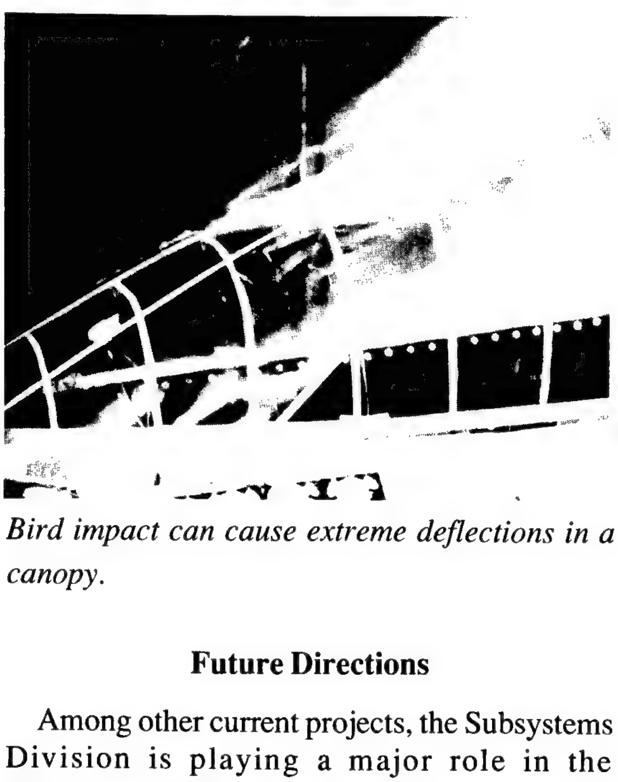
The Mobility Test Facility is known as the "Whirling Arm" because it rotates test articles over a circular track. Panels along the track can be removed or replaced to provide various surface conditions.

In 1980 a new test facility, the Mobility Development Laboratory, was opened at FDL. Research was conducted at this facility on air cushion systems for aircraft and ground support equipment and ground effects take-off and landing systems. A 44-foot whirling arm, moving around a circular track at speeds up to 50-mph, was powered by a 60-horsepower motor. Test models were attached to the end of the arm. A plexiglass static test platform was designed for close examination of the air cushion on test models; precise pressure readings could be taken as the model moved across the platform or was dropped from a crane.

The Landing Gear Test Facility, described earlier in this chapter, continues to serve as one of the world's most advanced facilities in its field. In recent years, the Transparency Test Facility has assumed increasing importance. It assesses damage to windshields and other transparencies exposed to birdstrike or other external threats, and several new canopies for advanced fighter aircraft have emerged from its work.



The Landing Gear Facility was orginally a Wright Field assembly shop.



Bird impact can cause extreme deflections in a canopy.

Future Directions

Among other current projects, the Subsystems Division is playing a major role in the development of frameless aircraft transparencies. Presently, windshields and canopies for high performance aircraft consist of transparent panels bent from previously formed flat sheets mounted in metal frames. High speed, low level missions have demonstrated the need for improved birdstrike resistance. The frameless transparency concept provides full utilization of the structural capabilities of impact resistant transparent materials. Panels are formed directly from plastic resins, eliminating the need for an edge reinforcing metal frame and allowing direct attachment to the airframe. A low pressure, long cycle injection molding process has been developed, allowing for the shaping of a wide variety of aircraft transparencies. This new technology will result in cost savings as well as improved structural integrity.

In support of FORECAST II, the Division expects to pursue work in such areas as heat exchangers and cryogenic coolers; hypervelocity crew escape technologies; improved tires and landing gear; and protection against non-nuclear combat threats and natural environmental hazards, including chemical and biological warfare. In the advanced development area, a mission integrated transparency system will be evaluated, and the Division will contribute essential equipment technology for hypersonic glide vehicles such as the National Aerospace Plane.

AEROMECHANICS DIVISION
FIM

AFTI/F-111 ADPO
(FIMF)

HIGH SPEED AERO PERFORMANCE BRANCH
(FIMG)

AERODYNAMICS
AERODYNAMIC HEATING
FLIGHT EVALUATION
FLIGHT PERFORMANCE

AERODYNAMICS AND AIRFRAME BRANCH
(FIMM)

AIRFRAME PROPULSION INTEGRATION
AIRFRAME AERODYNAMICS
AERODYNAMICS METHODS
COMPUTATIONAL AERODYNAMICS

EXPERIMENTAL ENGINEERING BRANCH
(FIMN)

MECHANICAL INSTRUMENTATION
ELECTRONICS
MECHANICAL SYSTEMS
AERO OPTICS INSTRUMENTATION
ELECTRICAL SYSTEMS

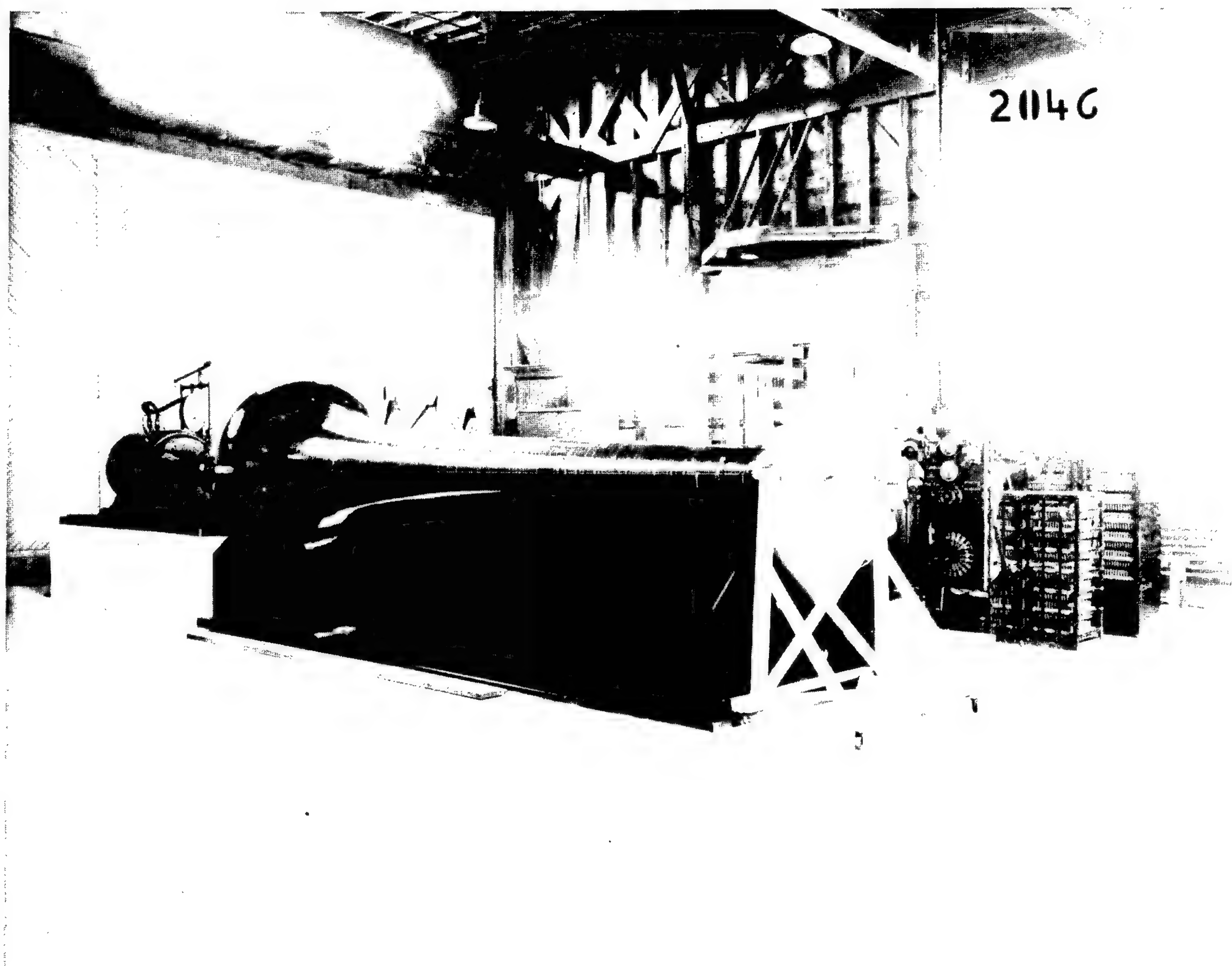
X-29 ADPO OFFICE
(FIMT)

STOL AND MANEUVER TECHNOLOGY ADPO
(FIMX)

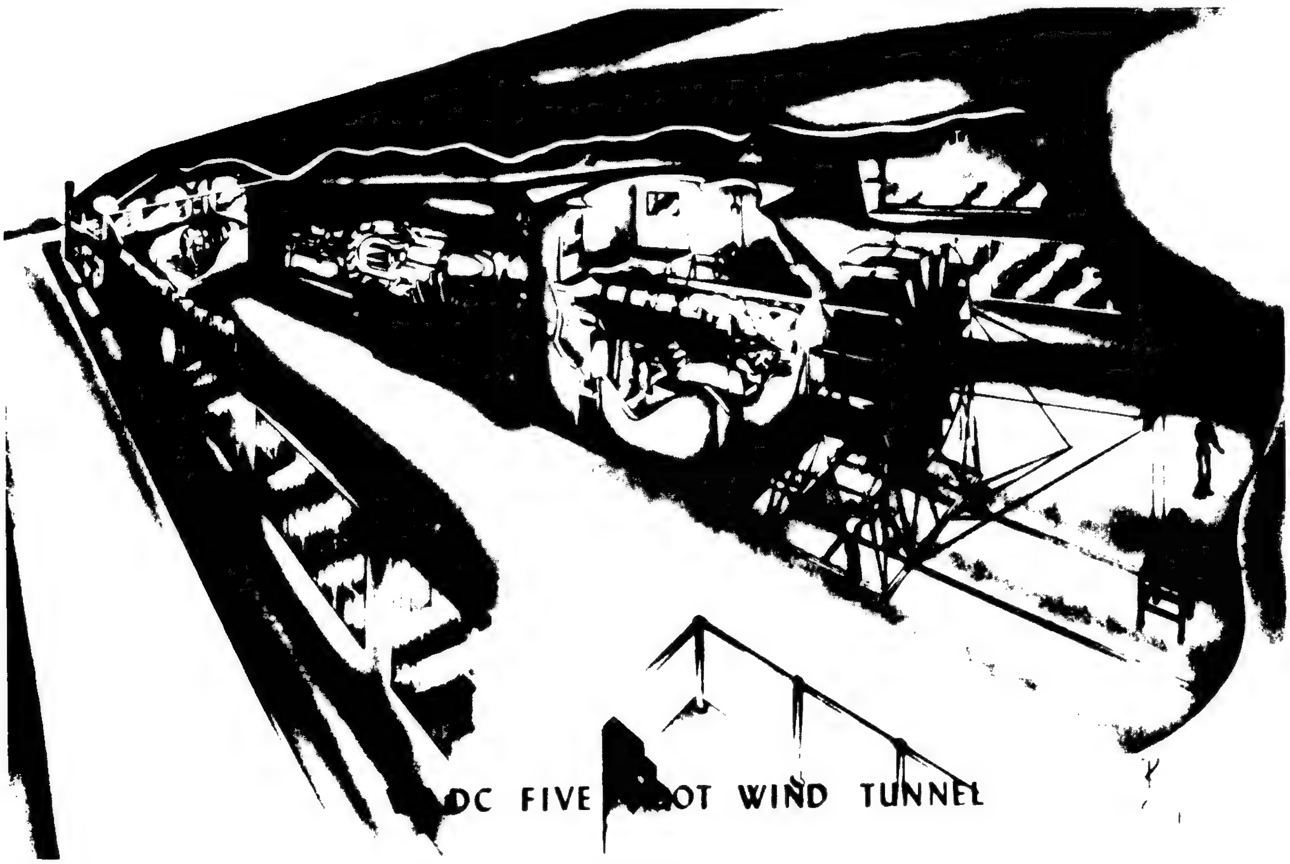
Aeromechanics

Today's Aeromechanics Division can trace its ancestry back to the Technical Services Office established at McCook Field in the early twenties. This office was responsible for the Army's first aerodynamic test facility, a fourteen-inch, 22-foot long wind tunnel built in 1918 and capable of generating a 453-mph wind. Although Langley Field has long claimed the honor of having conducted the first military wind tunnel test, in fact the first run of McCook's fourteen-inch tunnel occurred in March 1919, some eight months earlier than the Langley test.

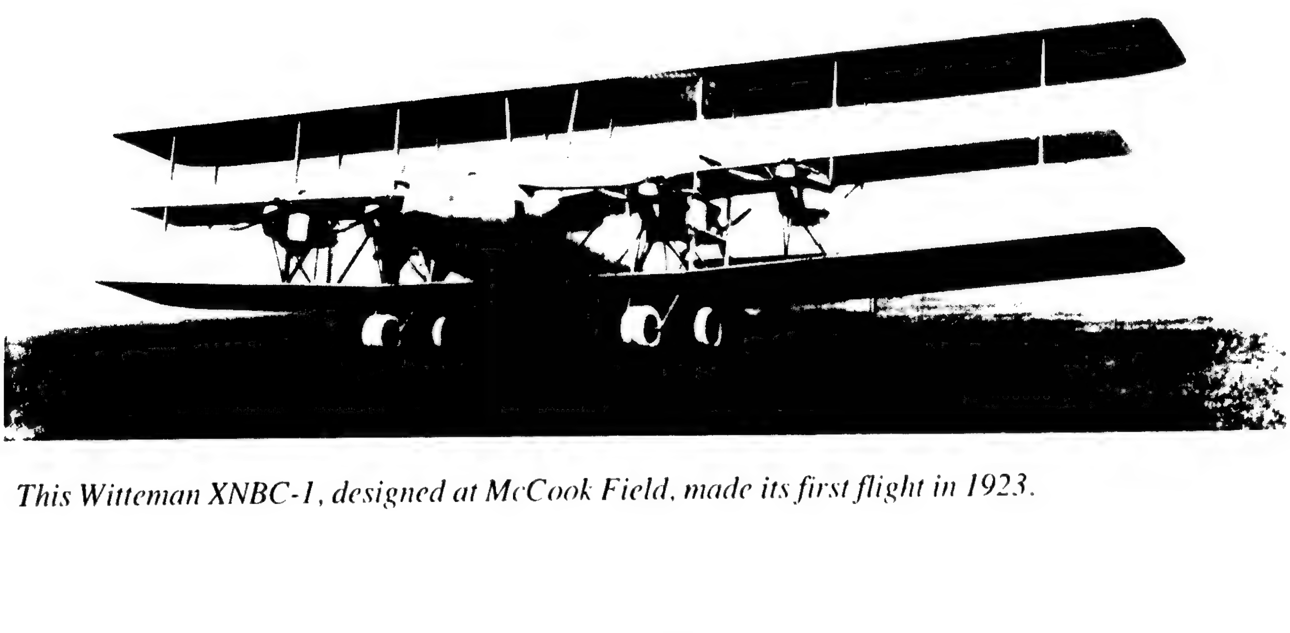
A five-foot wind tunnel, 96 feet long, was added in 1921; it could accommodate models up to 40 inches wingspan. The original electric suction fans could generate wind speeds of 275 miles per hour. One of the early projects tested in this tunnel was the Barling Bomber, at that time the world's largest airplane. The five-foot tunnel



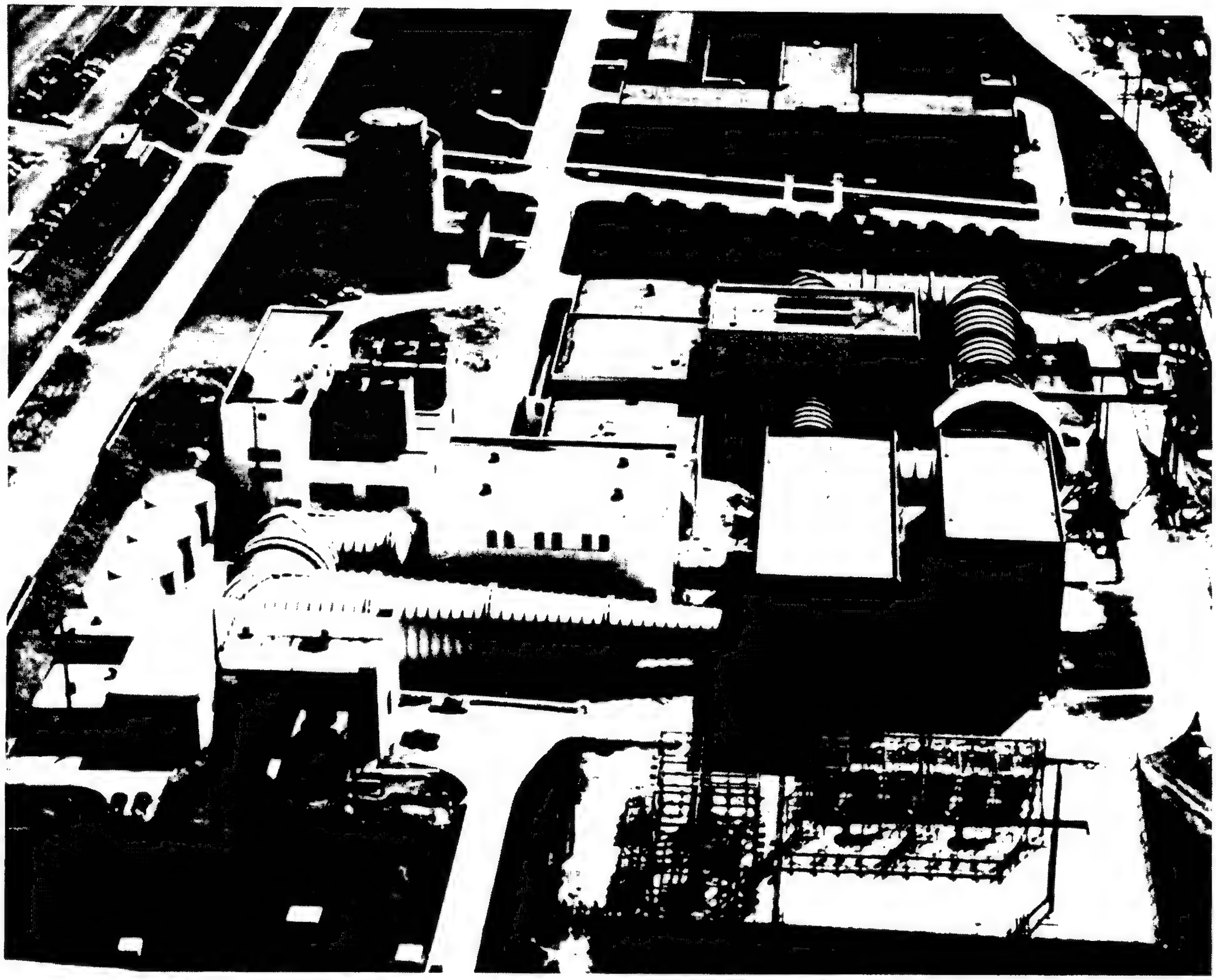
McCook 14-inch wind tunnel (1922).



Artist's conception of the Wright Field 5-foot wind tunnel. Note the similarity to the earlier McCook wind tunnel.



This Witteman XNBC-1, designed at McCook Field, made its first flight in 1923.

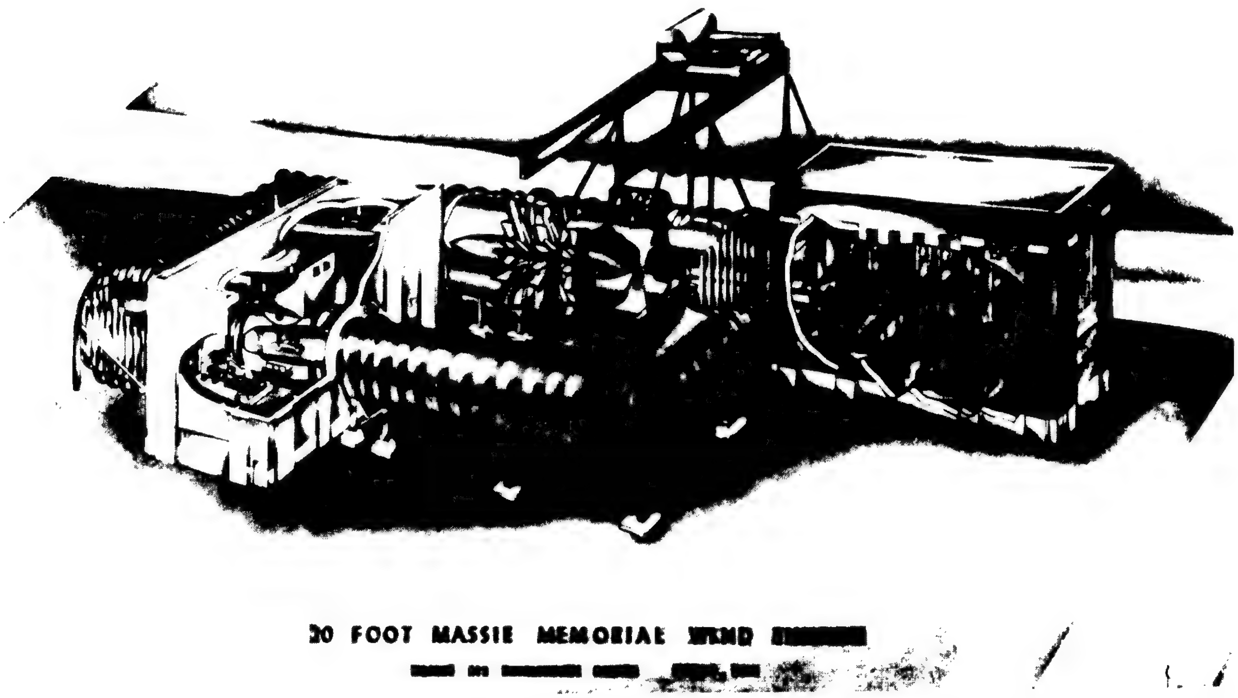


Aerial view: Massie wind tunnel on right, 50 MW test facility on left, and vertical wind tunnel on upper left.

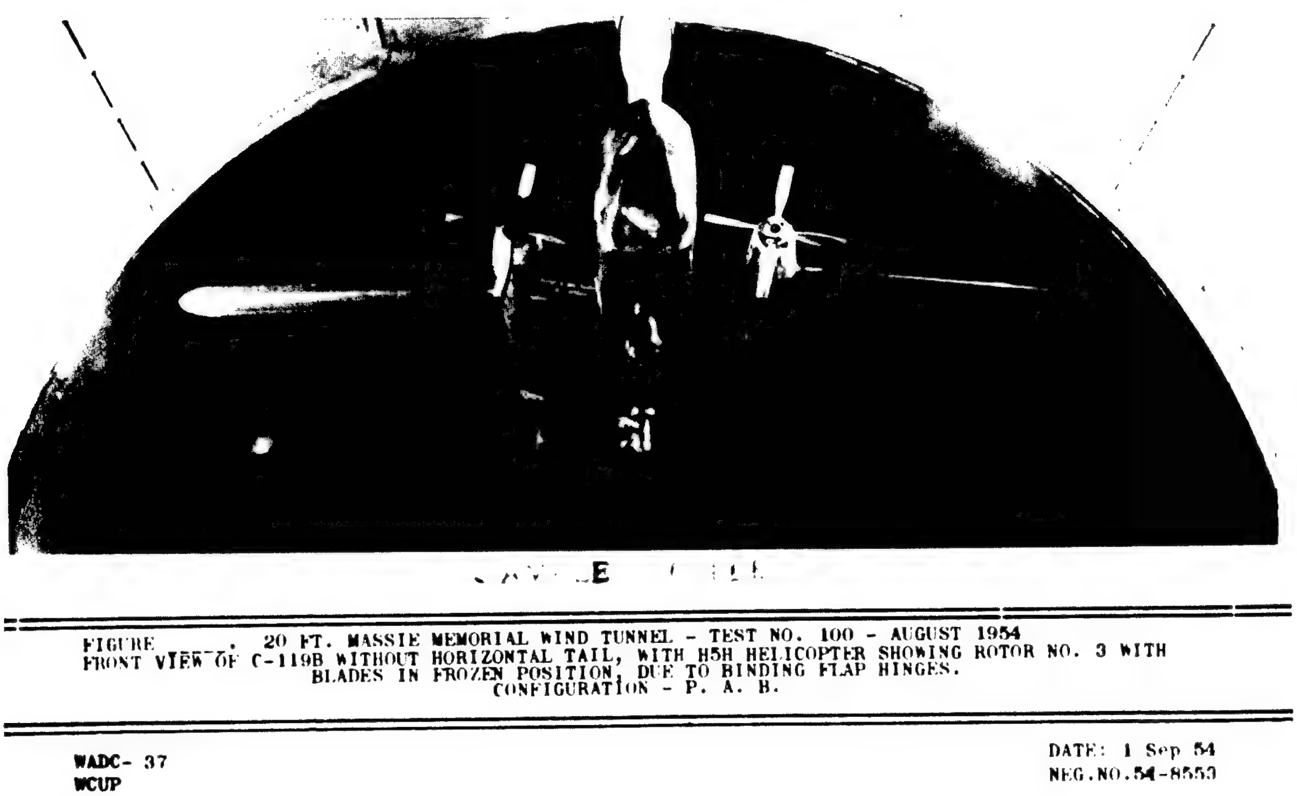
is a priceless link with the past: Orville Wright inspected it when it was constructed; all US fighter aircraft developed up until the early fifties were tested in the tunnel, and it has recently supported advanced projects like the X-24 aircraft. It is one of the oldest operational wind tunnels anywhere.

When facilities were moved to Wright Field in 1927, the Aerodynamics Research and Test Laboratory was established as part of the Engineering Division. During the thirties the Lab made substantial contributions to the theoretical and practical understanding of aerodynamics. Its facilities included the two wind tunnels already mentioned, and in 1939 the twenty-foot Massie Memorial Wind Tunnel was begun. After 1942 it was instrumental in the development of many World War II fighters and other aircraft. The B-58, for example, never would have flown without the hard work of the Aerodynamics crew.

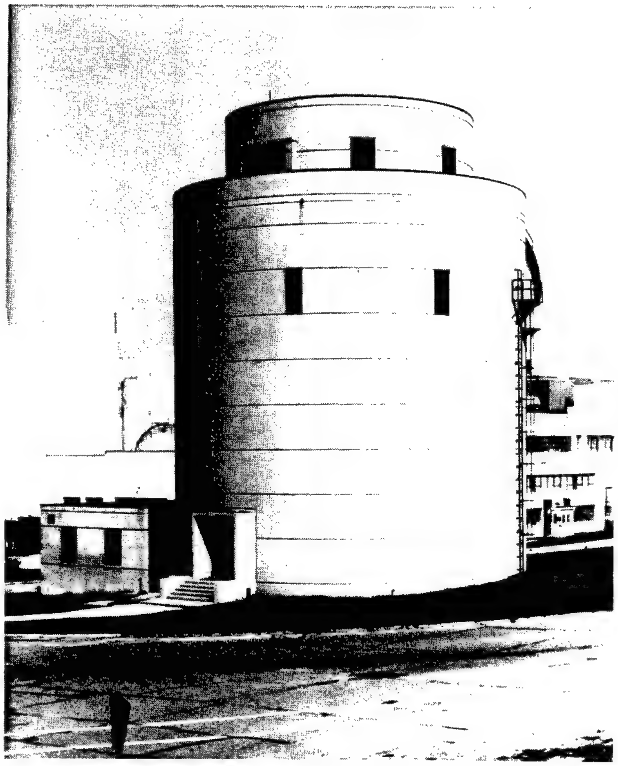
The 1950s saw new expansion far beyond the original mission of the Lab. The Wind Tunnel Branch then occupied the Building 24/25 complex as well as Buildings 26 (the two-foot transonic gasdynamics facility) and 27 (the vertical wind tunnel), and the five-foot tunnel was located in Building 19. The ten-foot transonic wind tunnel, in which the record-breaking aircraft of the 1950s were



The Massie wind tunnel, in use from 1939 to 1957, provided large-scale test capabilities for the Aircraft Lab.



Twin boom transport model (made of mahogany), tested in the Massie wind tunnel in 1954.

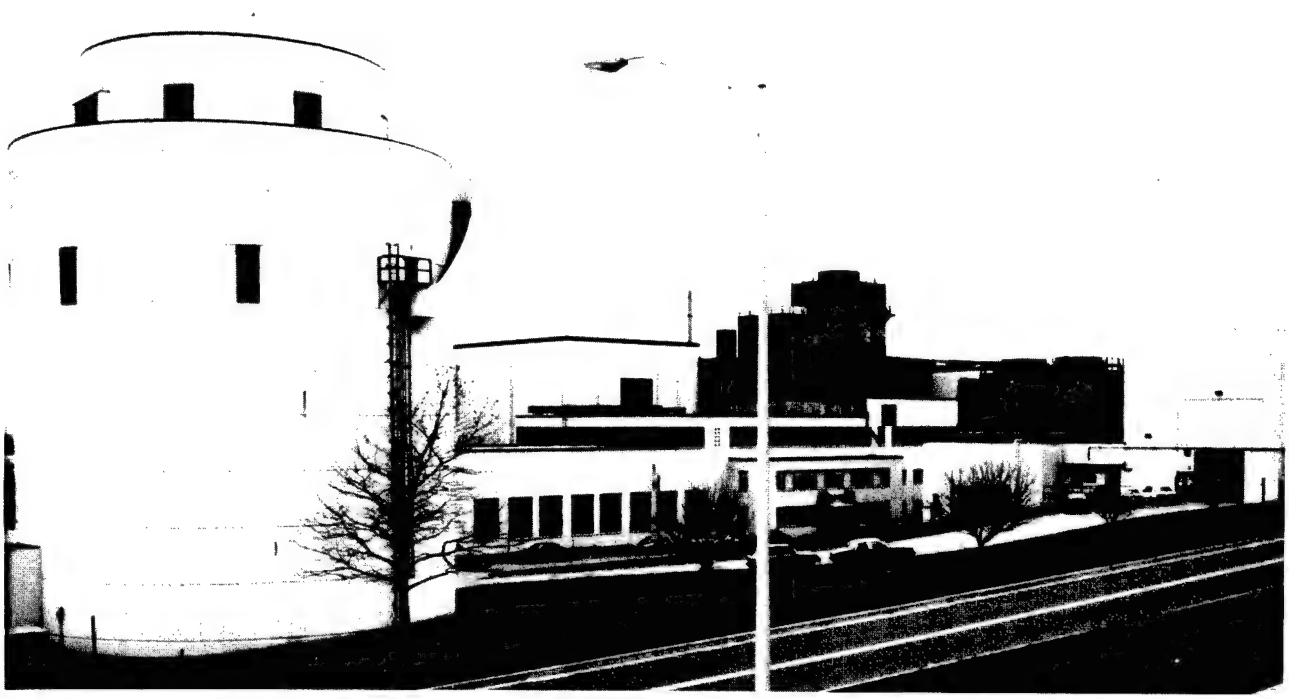


Vertical wind tunnel, built in the mid-1940s to test spin characteristics of aircraft.

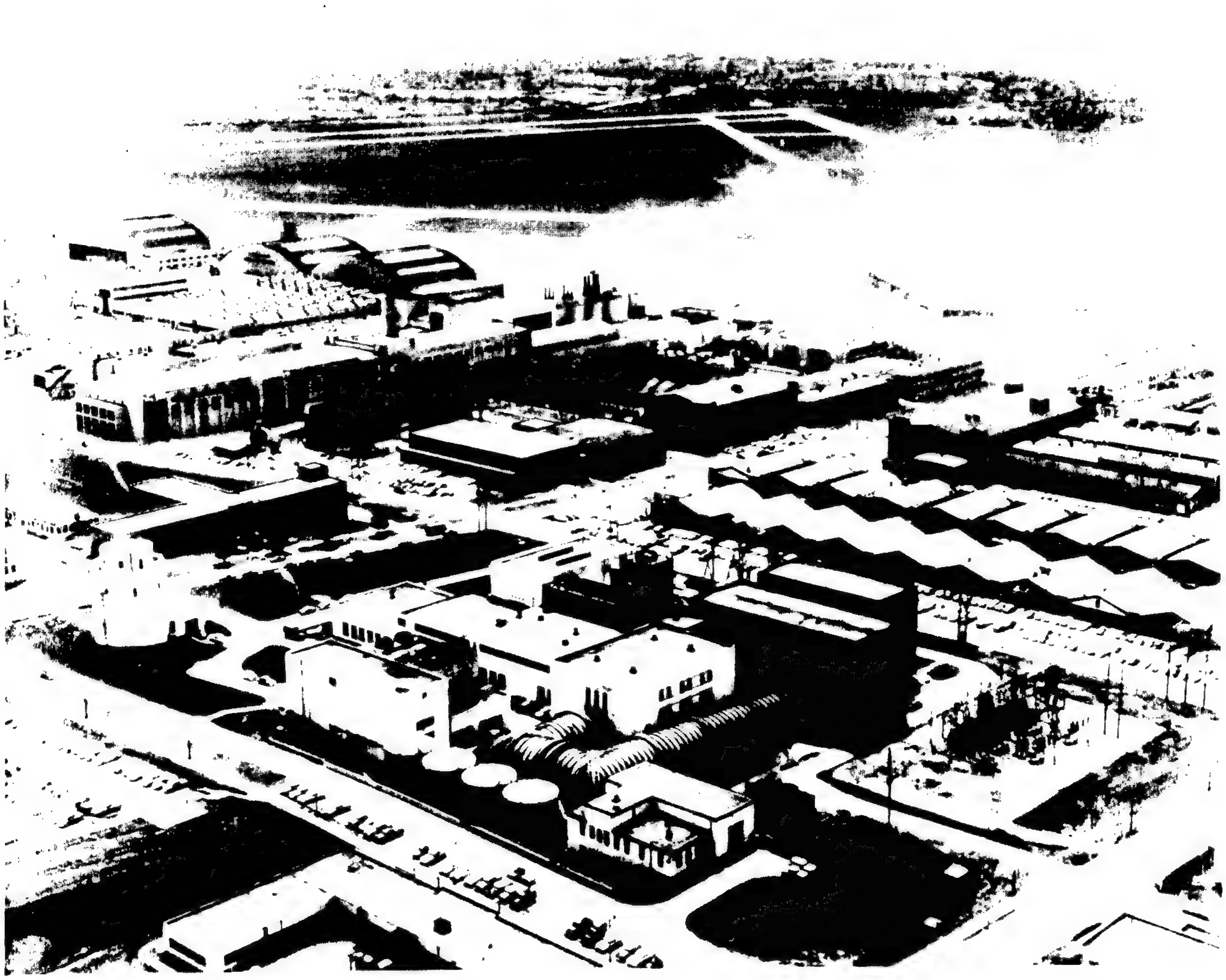
developed, was the best such facility in the world. It featured advanced slotted walls and adjustable sidewalls to establish superior flows. A six-inch supersonic tunnel, built in 1949, was vital in the design of many early supersonic aircraft. It was given to Ohio State University in 1958.

Security even in those days was very tight -- on one occasion, the base commander was denied entry because he did not identify himself according to procedures.

After the 1951 reorganization aeromechanics work was conducted by two branches, Aerodynamic and Wind Tunnels. The first of these was responsible for analytical and theoretical research, which was deemphasized during the fifties in favor of the more glamorous experimental wind tunnel efforts. In 1958 the two branches became one, and then a division of the new Flight Dynamics Lab. In the late sixties analytical research and wind tunnel experimentation achieved a better balance.



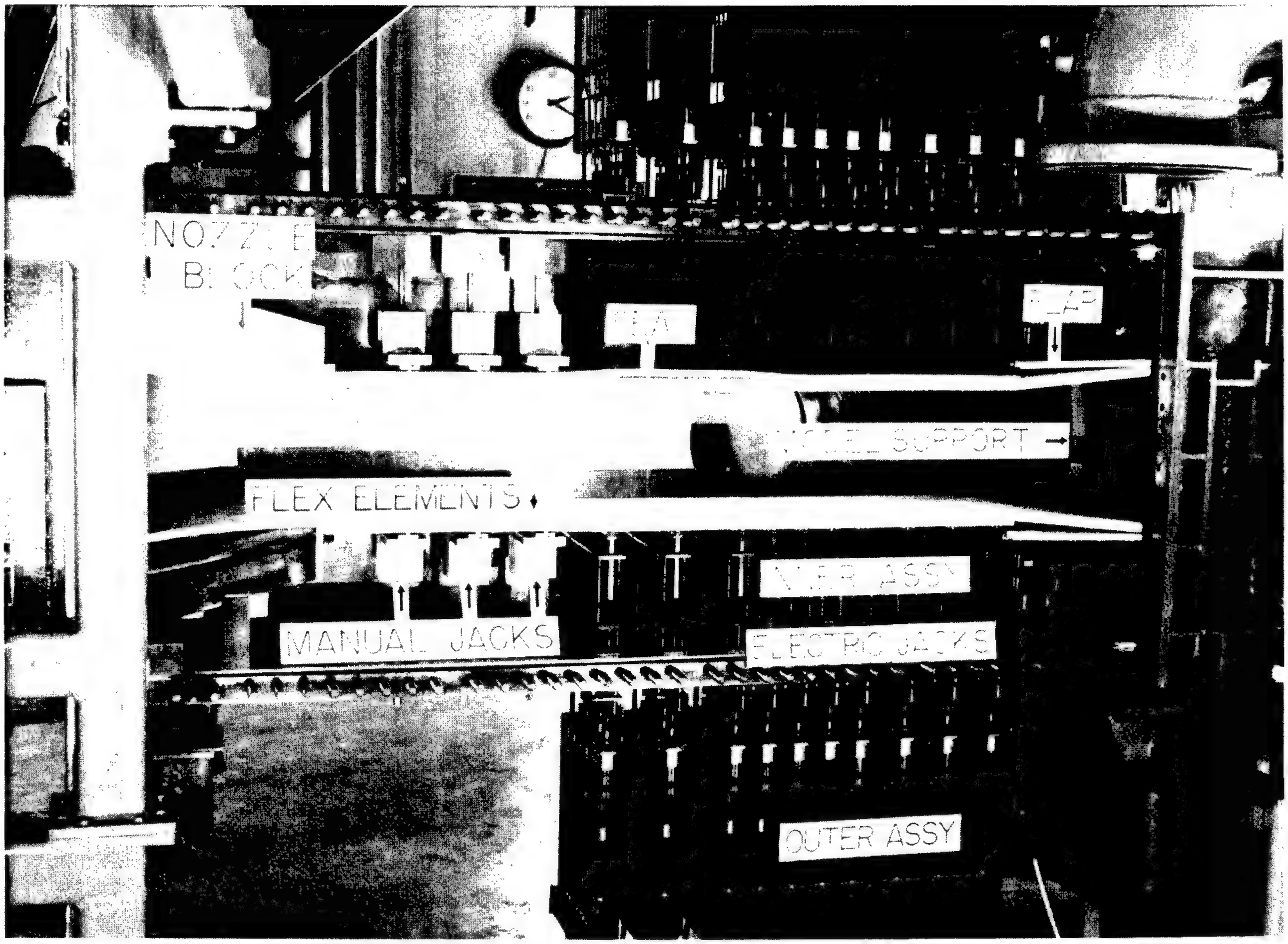
Building 27, 24, 26 and 25 of the Wind Tunnel Branch.



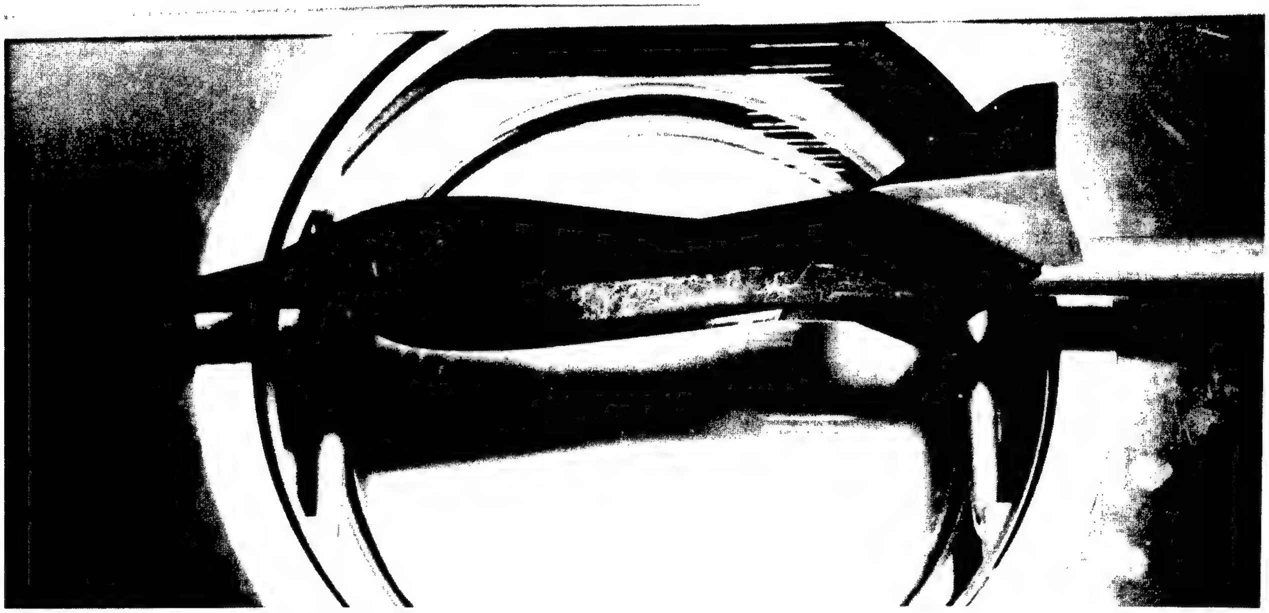
Aeromechanics wind tunnel complex, foreground. Note the DC-3s parked on the old flight line.

In 1958 the five-foot tunnel was given to AFIT but is still occasionally used by the Aeromechanics Division. The Massie Memorial Subsonic Tunnel, the ten-foot and the vertical wind tunnel were virtually phased out. Some of the components of the ten-foot tunnel were later incorporated into the 50 Megawatt Hypersonic and RENT (Re-entry Nose Tip) Facility, and others eventually went to the new Subsonic Aeronautical Research Laboratory (SARL). This facility is now named for the late Philip Antonatos, under whose guidance the Aeromechanics Division established its reputation for scientific rigor and careful validation of results and theories.

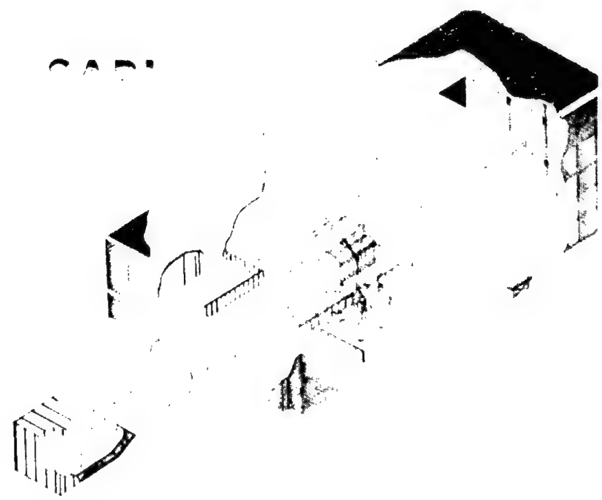
In the period between 1959 and 1983, experimental aerodynamic simulation and facility development emphasized high energy, high speed thrusts, and the subsonic and transonic facilities were deemphasized. Dr. Demetrius Zonars' leadership produced major breakthroughs in high pressure arc heater developments and real gas investigations. The four-megawatt, two-foot Electrogasdynamic Facility and the 50 Megawatt Hypersonic and Reentry Electrogasdynamic Facilities were added during the sixties, as was the Pebble Bed High Temperature Facility. A broad range of new flow visualization, aerothermal and thermochemical diagnostics and instrumentation



Some of the key elements of the 9-inch adaptive wall wind tunnel.

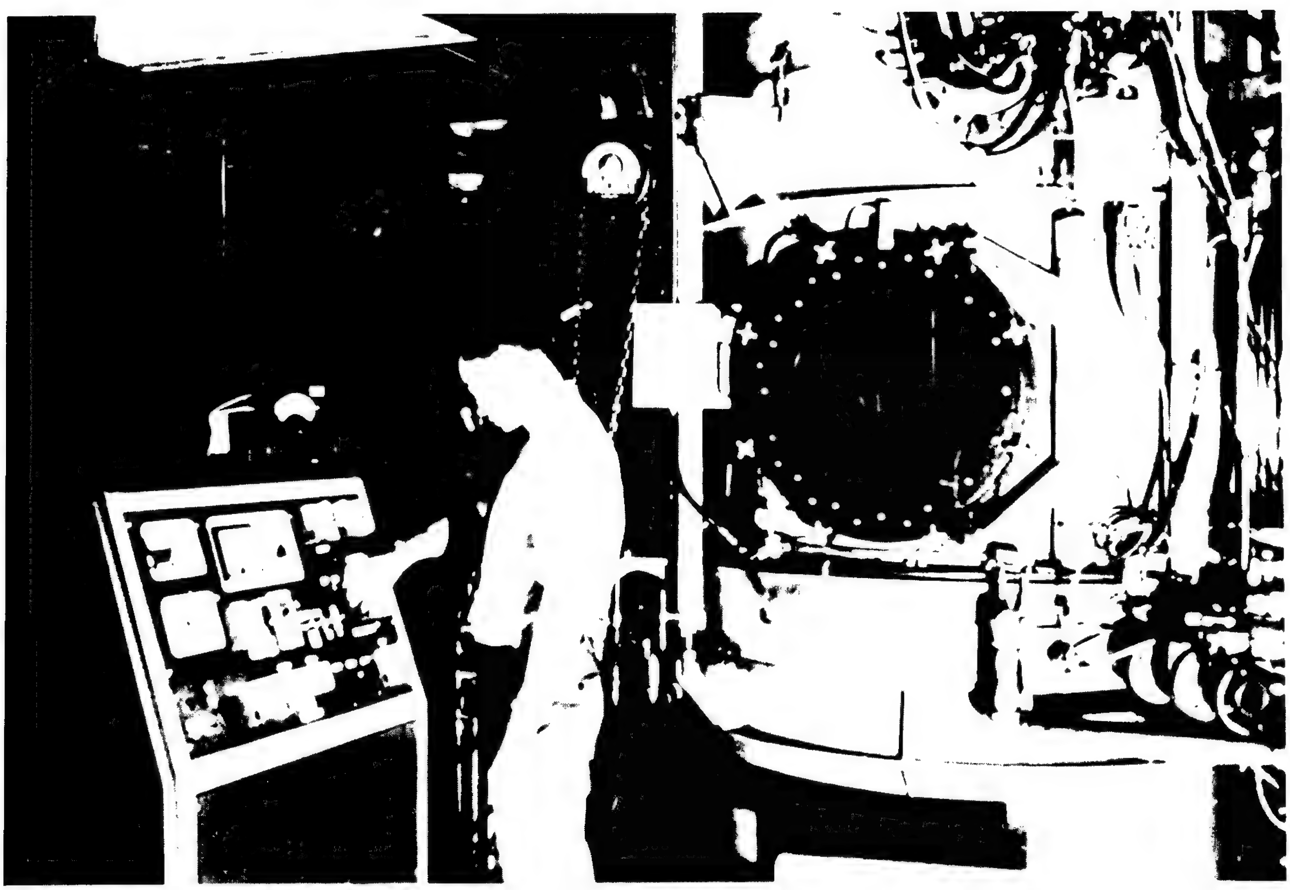


A micro fighter design being tested in the 9-inch adaptive wall tunnel.



were developed under the guidance of Daniel Parobek. This new generation of sophisticated high energy test flows strongly impacted development of lifting bodies, and initiated technology baselines for real gas aerodynamics and airframe and missile survivability under intense aerodynamic heating conditions. In 1971 the Aeromechanics Division inherited several facilities when the Aeronautical Research Laboratory was disestablished.

Schematic showing the large contraction inlet, the test section and the exhaust for FDL's newest wind tunnel, the Subsonic Aerodynamic Research Laboratory.



Engineer maneuvering an electron beam in the EGF to measure flow characteristics.

Building 254 housed two early high speed wind tunnels: the High Temperature Facility and the EGF.

Aeromechanics Division's Building 450, which houses four wind tunnels.

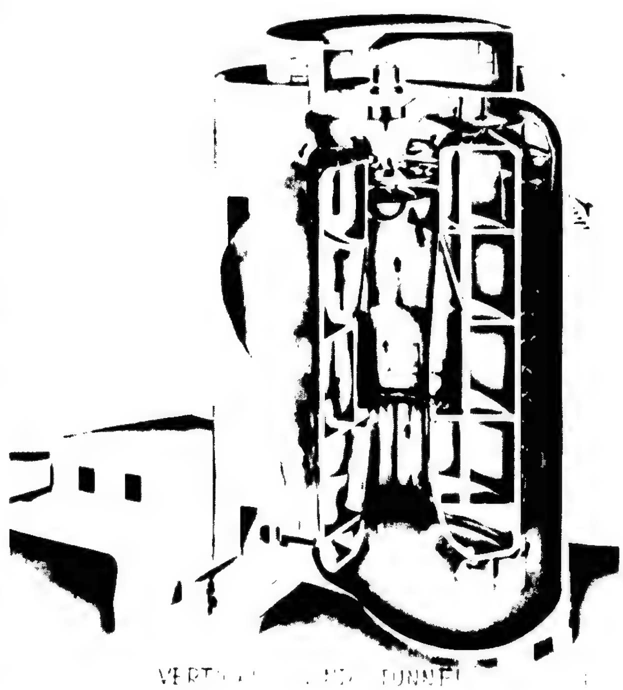
Subsonic Aerodynamics

Boundary layer control was one of the first major problems tackled by the Lab after World War II. The boundary layer is the airflow immediately adjacent to a wing or airframe, and if its characteristics can be controlled, lift is improved and drag is reduced. A YC-136 aircraft was tested in order to demonstrate the significant improvements that would be possible with more careful design attention to the boundary layer factor. The Stroukoff Aircraft Corporation, under contract, modified six C-123s; and a small Cessna airplane was modified for boundary layer control on the vertical and horizontal tail to demonstrate improvement of static margin (the range within which the aircraft is stable). RB-66 aircraft were also employed in boundary layer studies, and largely because of the division's work under the guidance of Philip Antonatos, this configuration was developed into the X-21 vehicle. A decade later, the data accumulated in this effort were invaluable in launching hybrid laminar control research -- the study of extremely thin layers of fluid flow within the boundary layer. This technology will be incorporated into the high-velocity commercial aircraft of the future.

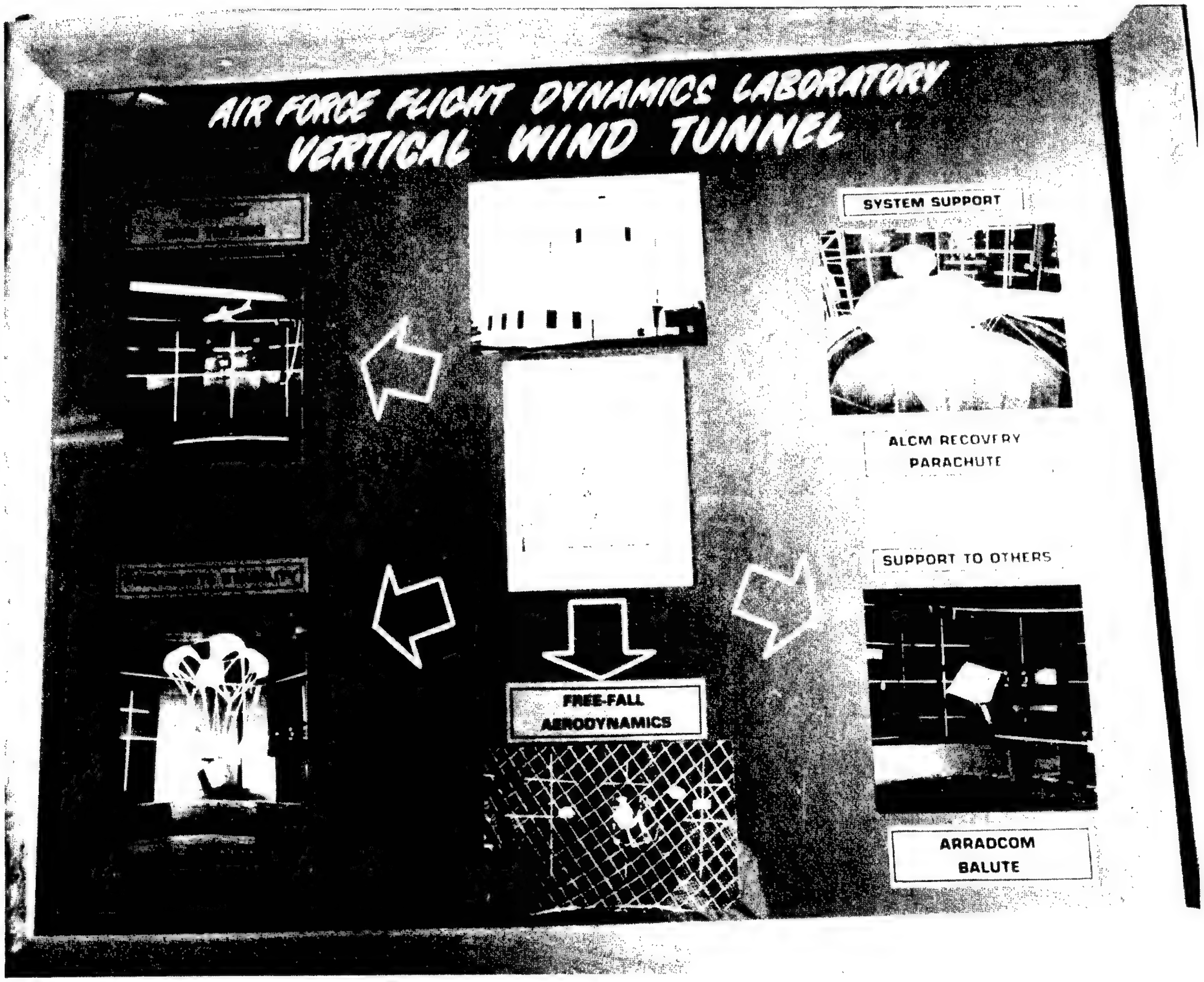
Programs carried out at the wind tunnel facilities investigated a number of possibilities for the extension of aircraft range. The external tank concept and in-flight refueling were proved feasible, and the optimum refueling drogue configuration (the relationship between the aircraft and tanker) was identified.

Experiments had already been conducted with tanks mounted on the wingtips of an F-80 (T-33), but this configuration was unstable. In conjunction with the Power Plant Lab, the Aircraft Lab developed a cheaper, more stable tank for the F-80. This tank could be easily disassembled and shipped in small crates. Buffet

Many new parachute designs were tested in the Vertical Wind Tunnel.



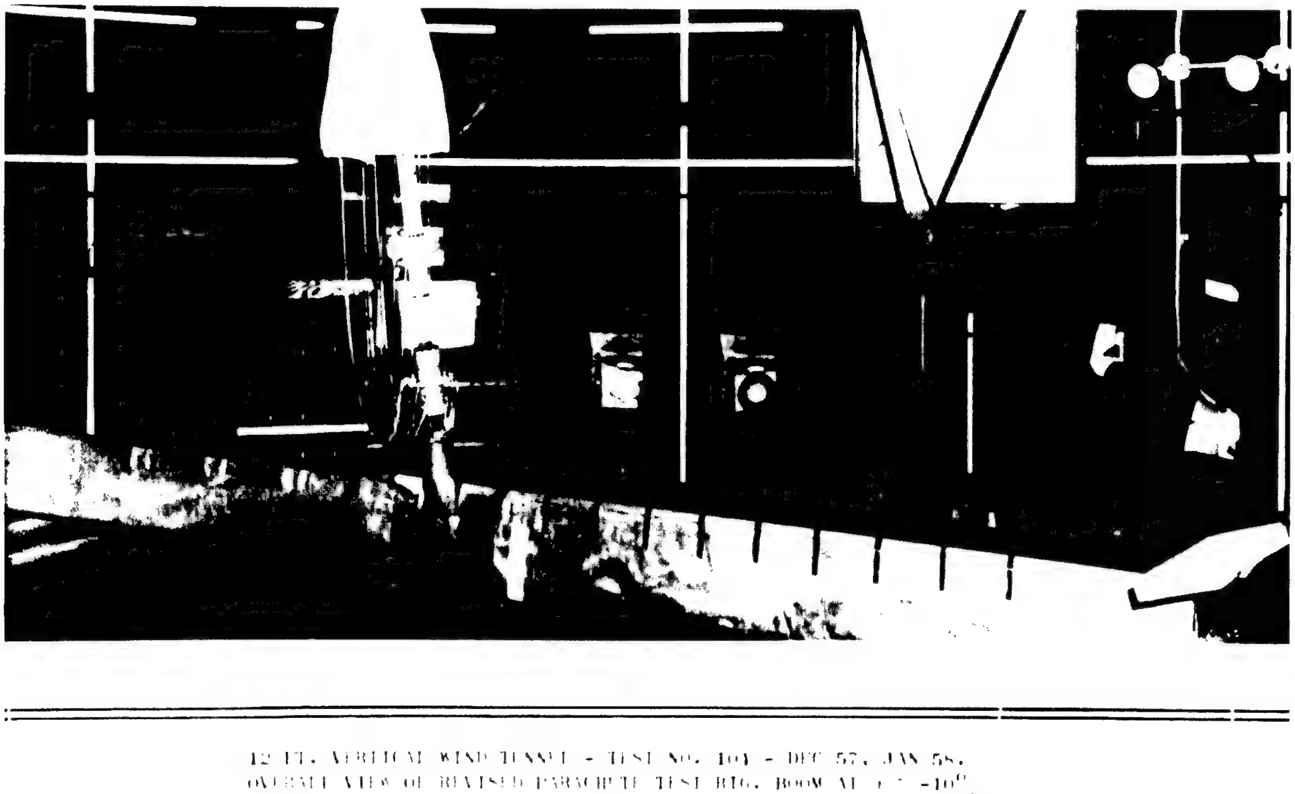
Artist's drawing, showing how air circulates around the inside of the vertical wind tunnel to provide air flow through the test section.



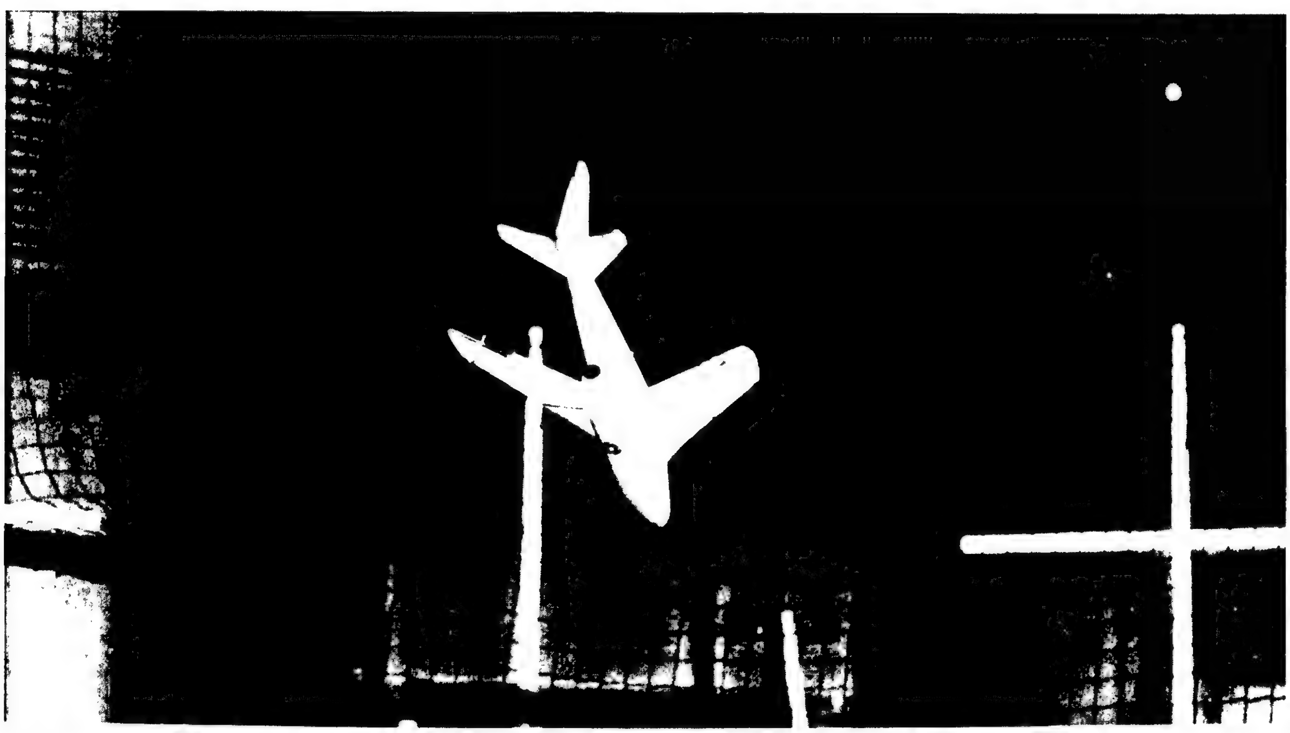
The vertical wind tunnel has tested many concepts and designs far afield from its original purpose.

(the irregular oscillation caused by turbulent wake) was eliminated, and drag was reduced. The new tank had an elliptical nose, a cylindrical center section, and a conical afterbody. The center section could be varied in length to increase capacity. This "Air Force Standard External Tank" began production in 1950 and will be familiar to anyone who served in the Korean War or afterward. The Standard Tank resulted in reduced shipping costs as well, since six disassembled tanks could be packed in the same crate formerly used to ship one tank. The Lab continued its research on external tanks as high-Mach number supersonic aircraft were developed.

The Lab's wind tunnels were also used for a number of exotic projects during the fifties. For example, a survival tent was tested for use in Arctic conditions; pilot escape or ejection systems were evaluated; and many varieties of airfoil were tested for stability and flutter. The vertical wind tunnel was built in 1942 for the purpose of examining the spin characteristics of aircraft such as experimental models of the X-1, X-2 and X-3, and the Century series fighters. Understanding of spin recovery procedures (that is, how to bring an aircraft out of an uncontrolled spin) was greatly augmented by these experiments, doubtless saving the lives of many pilots. The vertical tunnel was also used to test



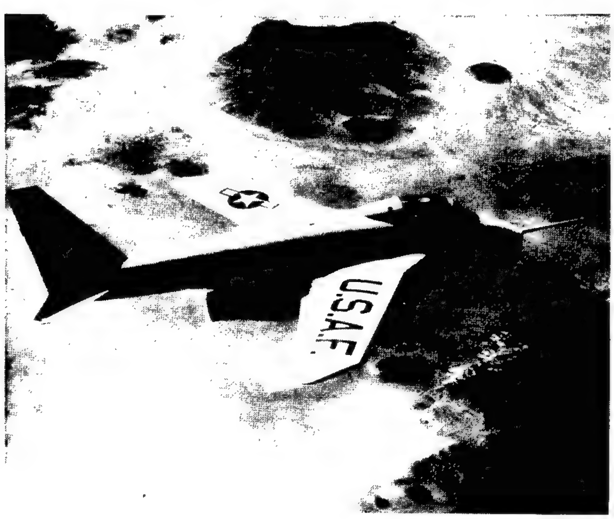
In 1958 air flow off the parachute test rig boom was modified to improve deployment of the parachutes.



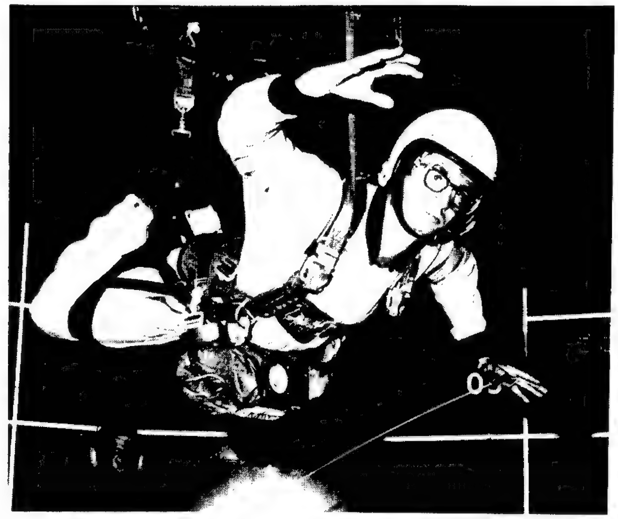
X-5 model undergoing spin testing. The large rings above the model trip control surfaces on the model using an electronically generated magnetic field.

An engineer releases a P-80 model during a spin test in the vertical wind tunnel.

drogue and equipment parachutes and for studies of pilot ejection from the F-94A. Early models of the X-5 were plagued by an inability to recover from spin, but tests in this tunnel showed that the problem could be solved by the addition of a ventral fin.



Since the X-5 wings could sweep forward or aft, the model had to be tested under many different aerodynamic configurations.

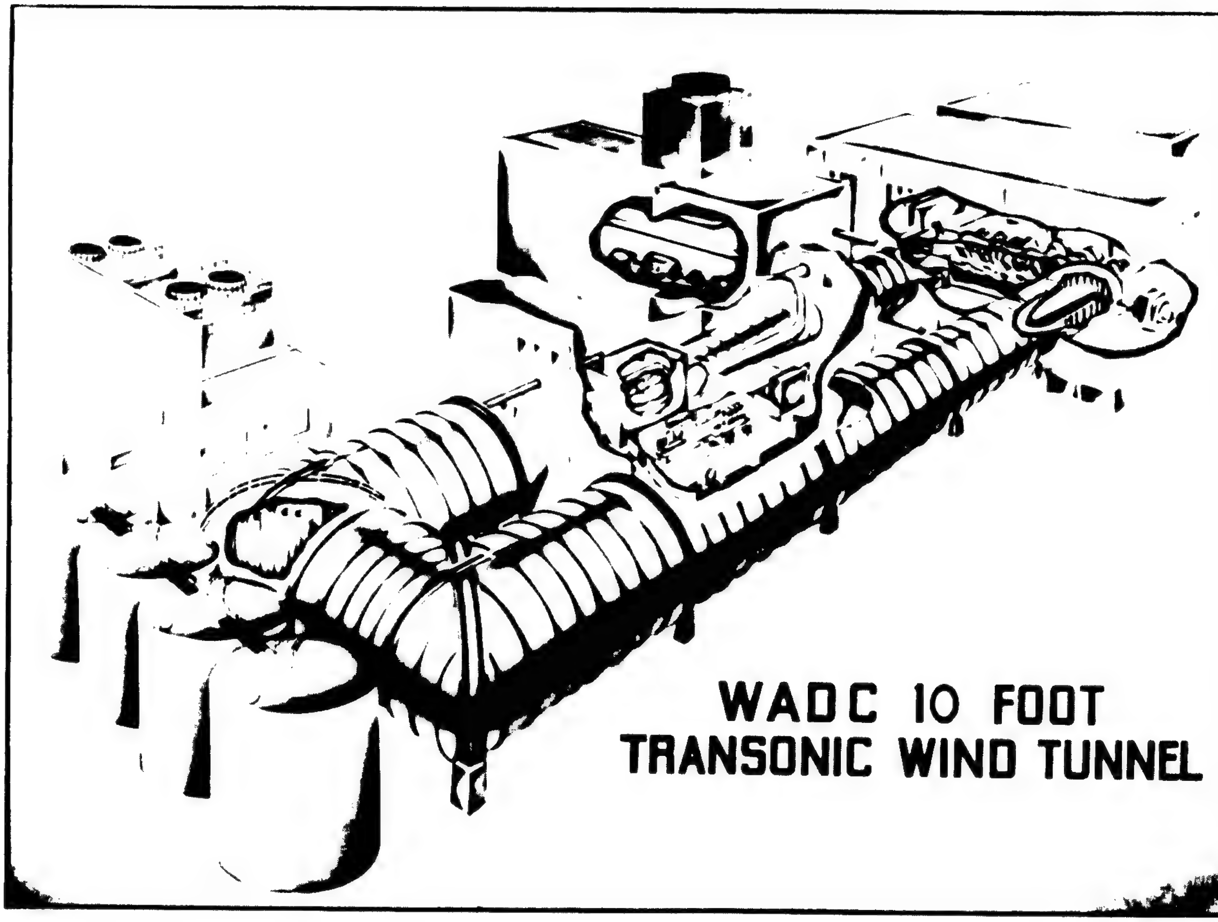


During the mid-1980s the US Army began using the vertical wind tunnel to train sky-diving students.

Advanced tactical fighter aircraft often fly at high angles of attack in the subsonic and transonic speed range. This leads to "separation," the breakdown of the flowfield into unpredictable vortices and turbulence, inducing shock vibrations. Experimental and theoretical investigations in recent years have attempted to enhance the subsonic and transonic aerodynamic, stability and control characteristics of current and future military aircraft by tailoring the forebody and wing geometries or by passive/active vortex flow devices.

Transonic Aerodynamics

The Lab was instrumental in solving many of the special problems inherent in the transition from subsonic to transonic speeds. Aerodynamic flows are encountered which can be explained only by nonlinear equations, and this was not fully feasible before the advent of computer analysis. The pioneer in transonics research was Dr. Bernhard Goerthert, who was the chief of aerodynamic research for the Germans during World War II. In the late forties he came to

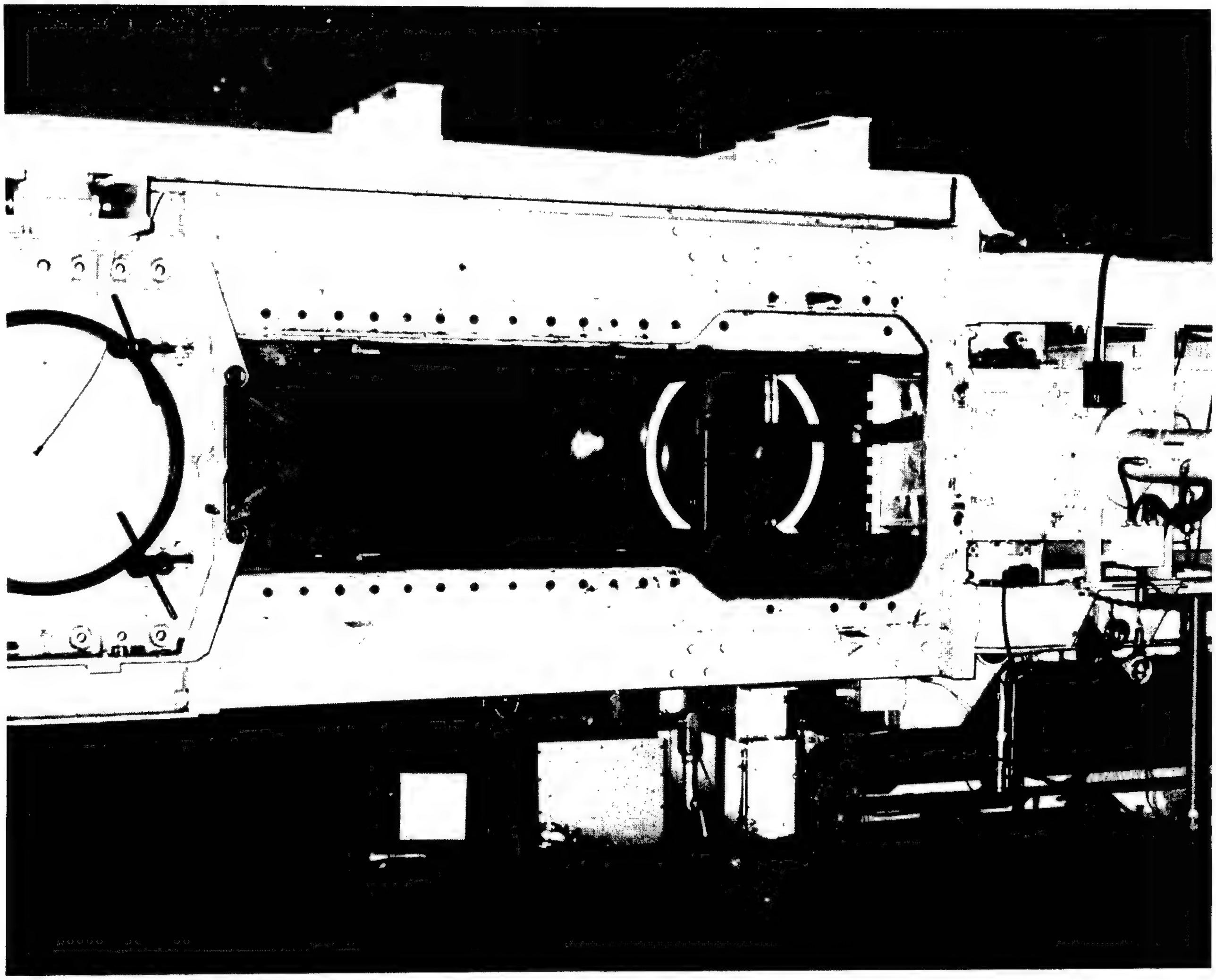


The ten-foot tunnel was built in 1947 to fill a void in transonic research facilities.

Wright Field via Project Paperclip and was put in charge of wind tunnel facilities. One of his early projects was the drag rise phenomenon, which was poorly understood until Wright Field's aerodynamic engineers studied it and recommended configurations that made the F-111 and similar aircraft possible. Drag rise is a sudden increase in wing drag when shockwaves occur. The ten-foot transonic wind tunnel saw the testing of dozens of weapon systems during the fifties, including the Bomarc, Snark, Rascal, F-101, F-102, Matador, Navaho, and the A4 heat-seeker, and especially the B-58.

Supersonic Aerodynamics

Since 1951 the Lab has concentrated on improving the supersonic regime for fighters, bombers and guided missiles. A two-foot supersonic wind tunnel was installed in 1951 to test for such problems as the instability created by boundary layer and shock interaction, and the "buzz phenomenon" -- a high-frequency oscillation that can damage the nose of an aircraft or missile. These studies also contributed to the improvement of wind tunnel design itself.



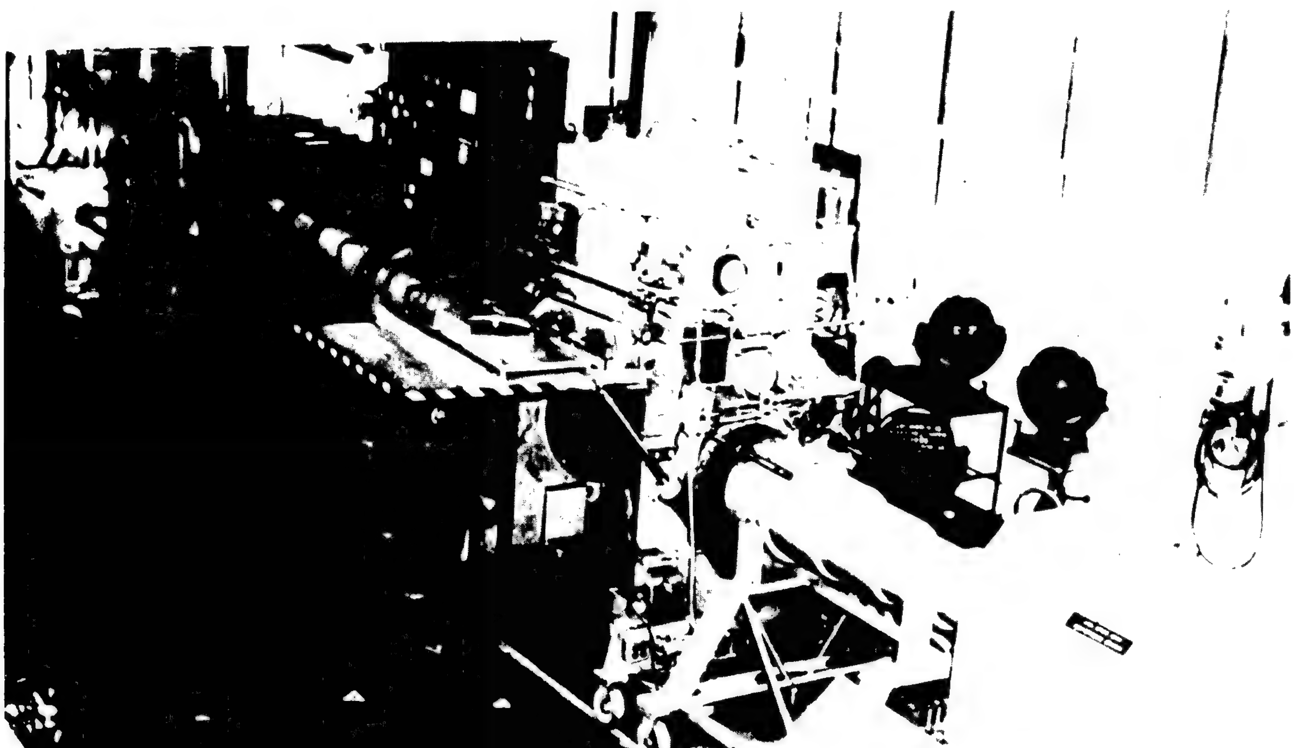
Nozzle of the Trisonic Gasdynamics Facility.

During the mid-fifties the Lab moved beyond direct wind tunnel experimentation to mathematical methods of predicting drag on proposed aircraft. WADC Technical Note 57-28, published in July 1957, was a milestone in the analysis of jet exit and other parameters involving aerodynamic pressures on vehicle bases. In 1958-1959 Laboratory resources were devoted to the Alpha Draco Program, an effort to develop a boost glide vehicle which could operate in the Mach 4 range. Eventually three Alpha Dracos were launched from Cape Canaveral, and demonstrated the feasibility of such vehicles for further research into the hypersonic regime. Alpha Draco soon evolved into the Boost Glide Re-entry Vehicle (BGRV) program, and a number of BGRVs were launched from Vandenberg AFB. Engineers at FDL foresaw, a quarter of a century ago, that boost glide technology would eventually be the direction taken by aerospace vehicle design. The boost glide vehicle, familiar to most people in the form of the Space Shuttle, is an aircraft launched into the upper atmosphere or into orbit by rockets or jets. It returns to earth by gliding with little or no jet propulsion. The 122M, the Aero Ballistic Re-entry System, and the Aero Ballistic programs also benefitted from this project.

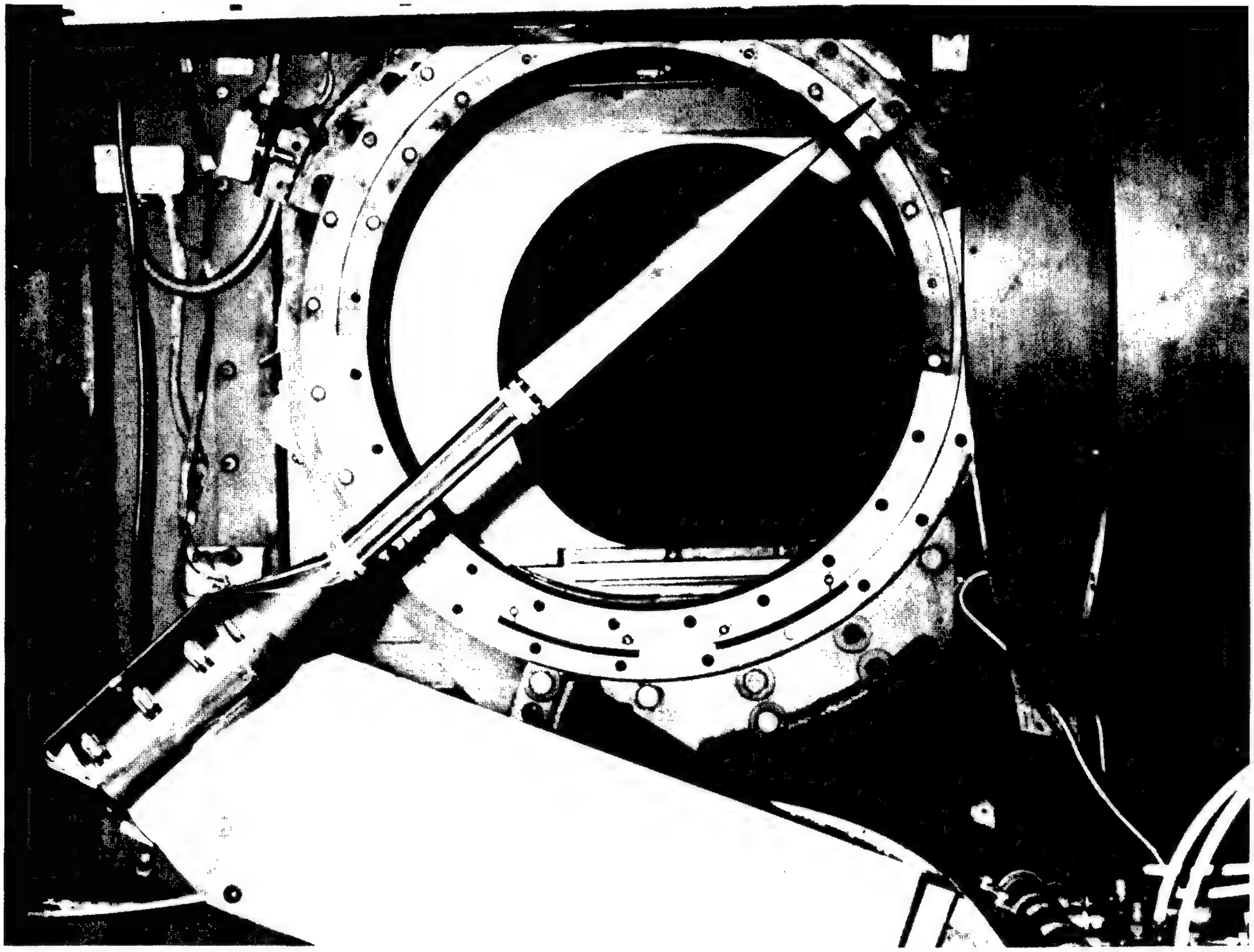
Aerodynamic research also has application to missiles, which became a primary concern of the Department of Defense in the 1950s. Since nuclear missiles are rather heavy and blunt, the configuration of the nose tip is crucial to the vehicle's range, speed and performance. The Flight Dynamics Lab undertook the first serious study of blunt body aerodynamics, and continued to lead this field in the following decades. At the beginning of the 1980s, for example, the division's team of Yoshihara, Daniels and Draper developed the blunt body spike later used on the Trident missile. They investigated the influence of Reynolds number (a coefficient used to indicate the scale of aerodynamic flow) and Mach number (velocity) on flow characteristics at supersonic speeds over various blunt bodies with slender spikes. Drag and flow were measured, and the effects of spike fineness ratio, geometry and angle of attack were studied. The range of the Trident missile was extended approximately 300 nautical miles by this effort.

Hypersonic Aerodynamics

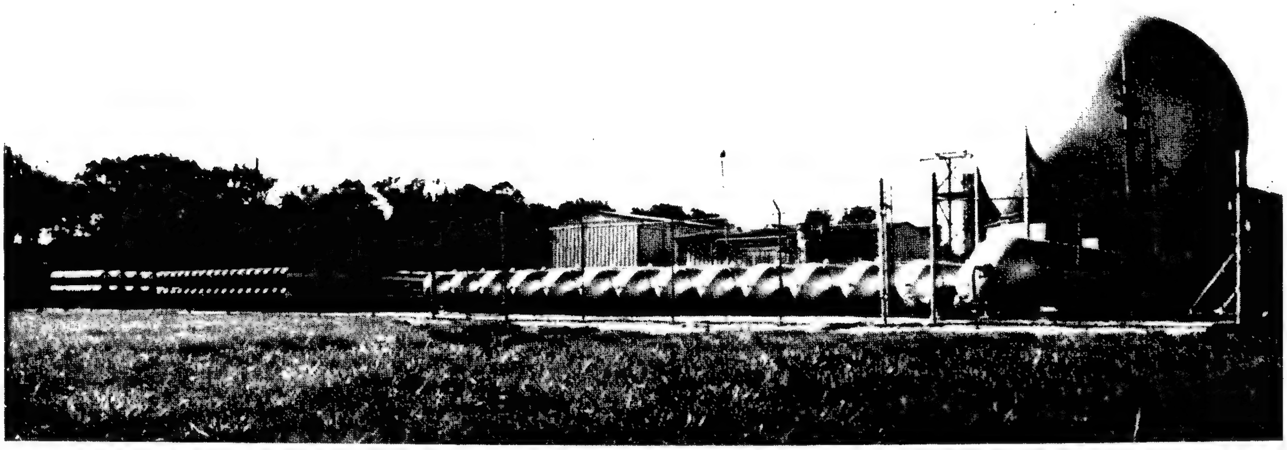
In the last months of World War II Germany began construction of a 1 meter by 1 meter hypersonic wind tunnel in the Bavarian Alps. Discovered by American investigators, this tunnel (later moved to France) was used as a model for the hypersonic facility at Arnold Engineering Development Center. Similar



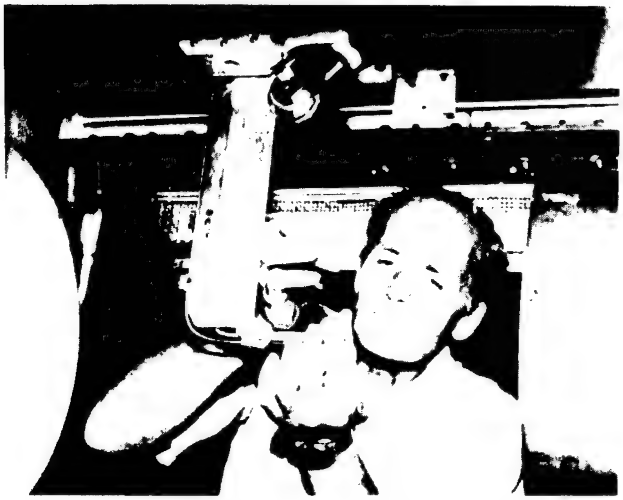
The 20-inch hypersonic wind tunnel is a blow-down type facility using an upstream high pressure to a downstream vacuum.



Aero Configured Maneuvering Re-entry Vehicle (ACMRV) model in test section of the 20-inch hypersonic wind tunnel.



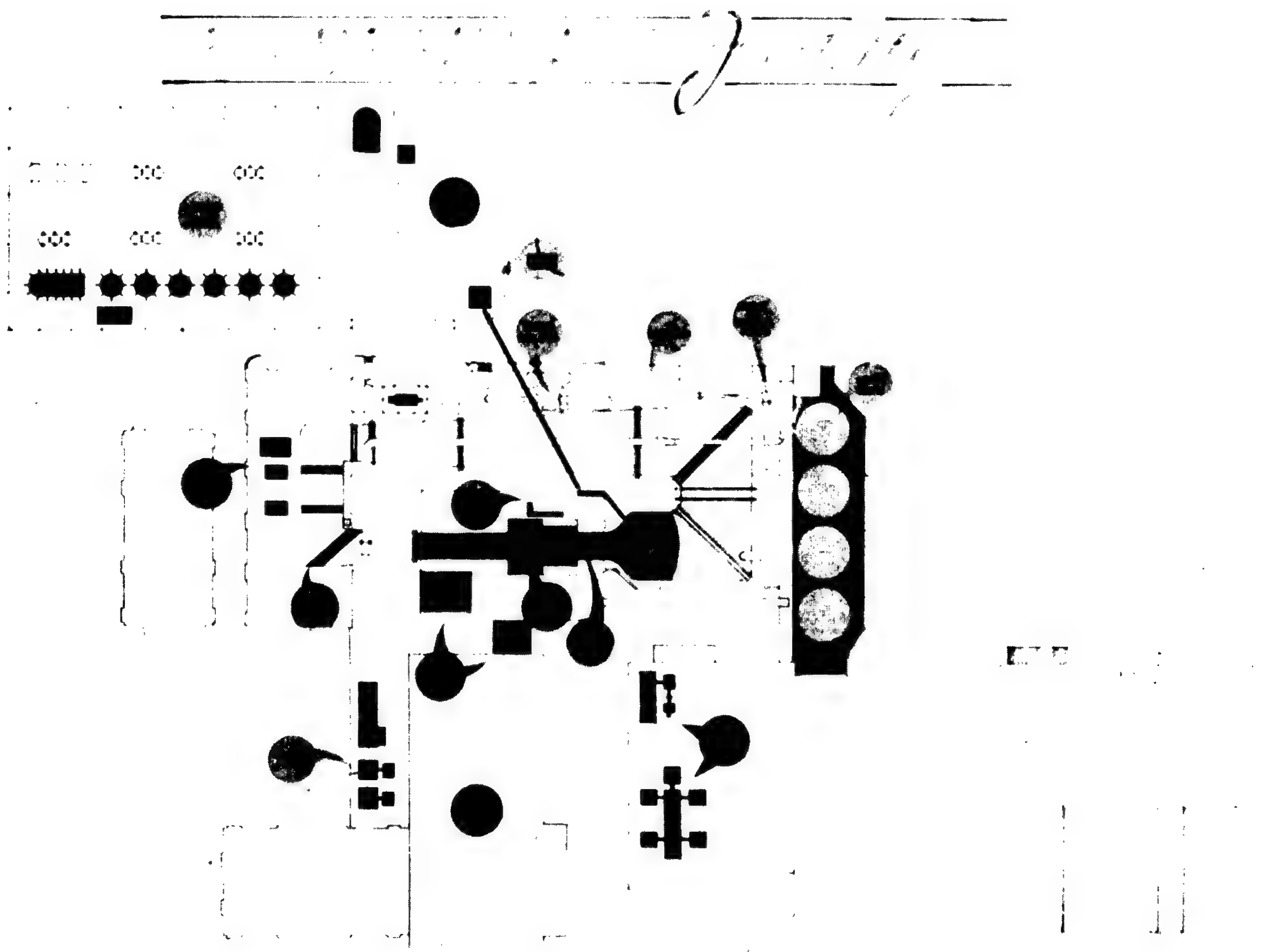
High pressure bottle farm in front of the large vacuum sphere used by the 20-inch hypersonic, Mach 3, and Mach 6 wind tunnels.



A technician adjusts a probe in the test section of the 20-inch hypersonic wind tunnel.

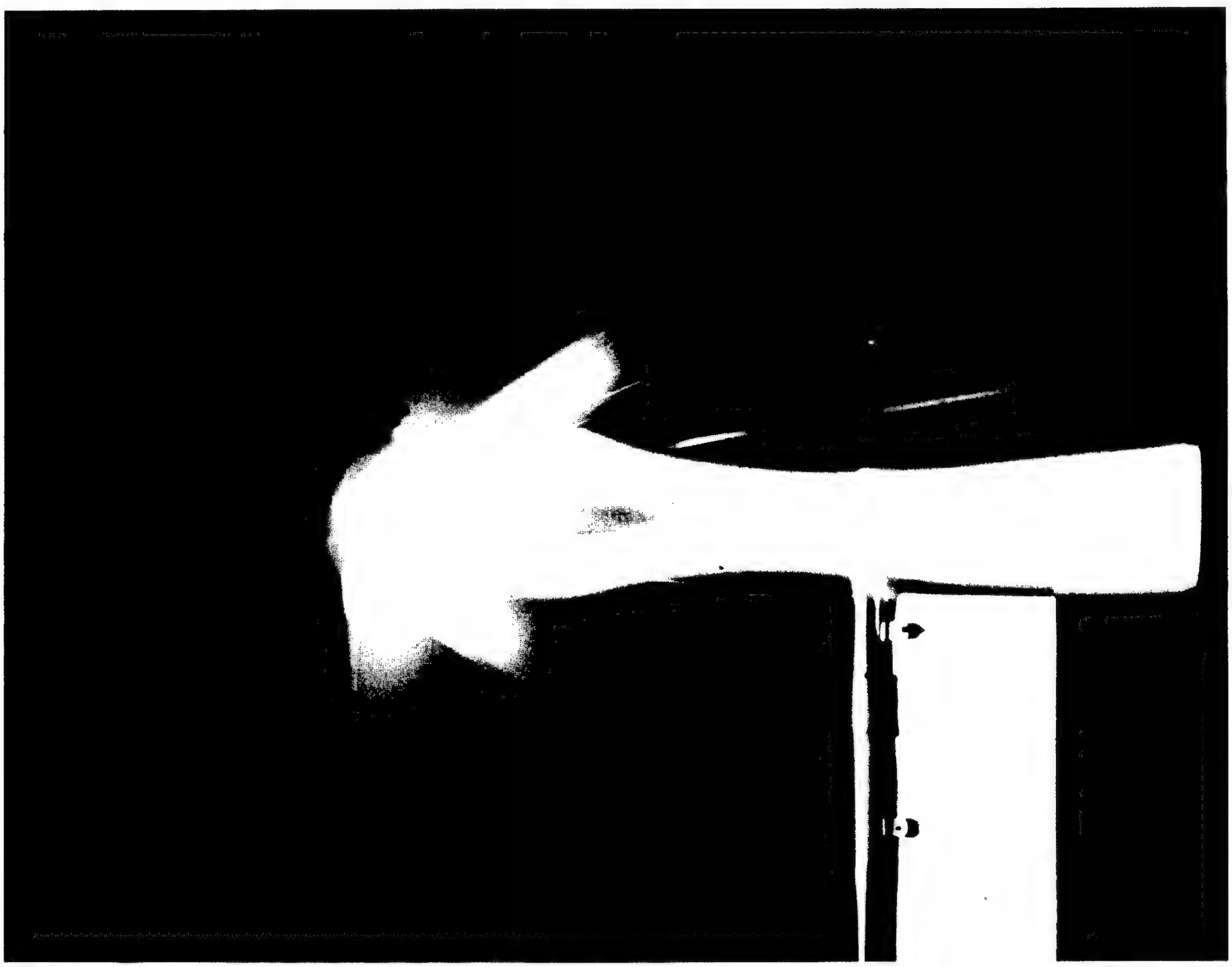
tunnels were built at Ames and Langley, and during the 1950s most hypersonic aerodynamic research was conducted at these facilities. The Aerodynamic Lab at Wright-Patterson designed the models tested in these wind tunnels. Wright Field's twenty-inch hypersonic wind tunnel came on line in time to participate in several advanced programs. However, "real-world" hypersonic data were not available until the successful flights of Project ASSET in 1963 and 1964.

In the late fifties the Lab faced one of its greatest challenges. Aerospace research was beginning to focus on the development of re-usable glide vehicles (that is, what we now call the space shuttle), and the problems to be solved were of an entirely new order. The harsh environment of space, together with the extreme



Schematic of the hypersonic test leg of the 50-megawatt facility.

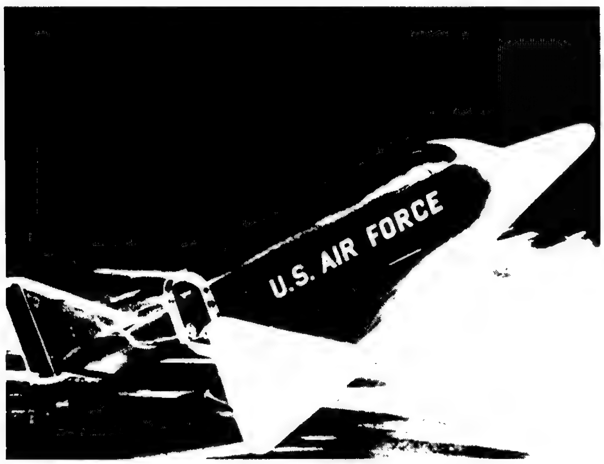
stresses of re-entry, required radically new materials and configurations. Conditions in space could not be simulated by on-the-ground testing, and therefore the Lab took a very conservative approach toward design philosophy, particularly in regard to vehicle weight. The Lab was directed to explore four areas: structures, aerodynamics, aerothermodynamics and aerothermoelasticity. The Dyna-Soar (X-20) commenced in 1959. Project ASSET (Aerothermodynamic/elastic Structural Systems Environmental Tests) was initiated when the first contract was awarded to McDonnell in April 1961. During this period NASA and the Flight Dynamics Laboratory competed to produce the first practical hypersonic glide vehicle. Several generic families of vehicles were designed and tested in wind tunnels. Research focused on lifting body designs for low earth orbit, and the Lab developed configurations capable of high aerodynamic and performance efficiency during reentry. High lift-to-drag designs were identified as desirable, and were used in Project ASSET and the Dyna-Soar. A high lift-to-drag ratio means greater efficiency, because less power is needed to lift the vehicle; but it must be designed to extremely fine tolerances. NASA's efforts eventually led to the successful space shuttle program, and support from the Flight Dynamics Lab helped make the shuttle possible.



Leading edge specimen being tested in the hypersonic test leg of the 50-megawatt facility.

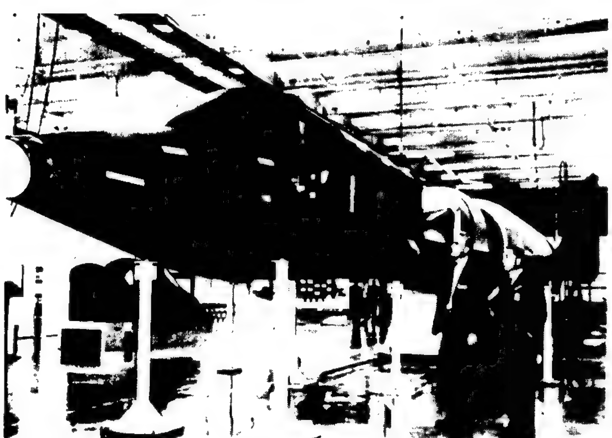
The Dyna-Soar Program

Even before the first X-15 rolled out, the aerospace research community called for development of an advanced orbital lifting re-entry vehicle. NASA Ames proposed a Mach 10 demonstrator; a week after the launching of Sputnik, the Air Force consolidated three programs (Robo, Brass Bell and Hywards) into the "Dyna-Soar" SPO (System Project Office). The name was derived from "dynamic soaring" and the program was later designated the X-20. The Air Research and Development Command assigned major responsibility for Dyna-Soar to WADC, and nine contractors submitted proposals. Four contracts were awarded (to Martin, Bell, Boeing, and Vought) and the primary contract went to Boeing. William Lamar of the Flight Dynamics Laboratory was appointed technical director, and worked closely with John Becker, a prime mover of the X-15. When work commenced in 1959, Dyna-Soar looked like a winner.

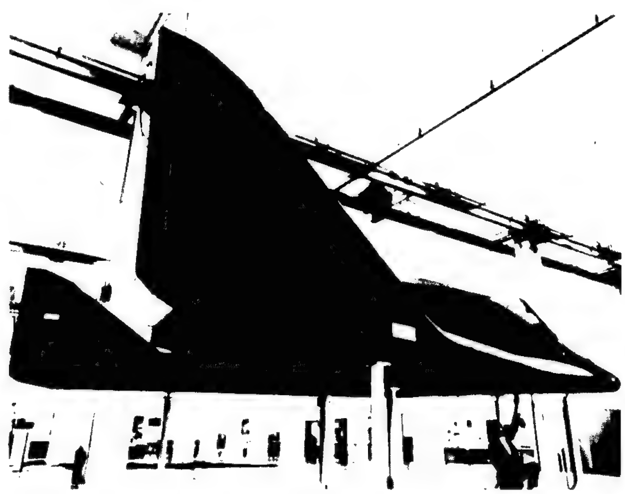


Artist's conception showing the X-20 Dyna-Soar beginning re-entry into Earth's atmosphere.

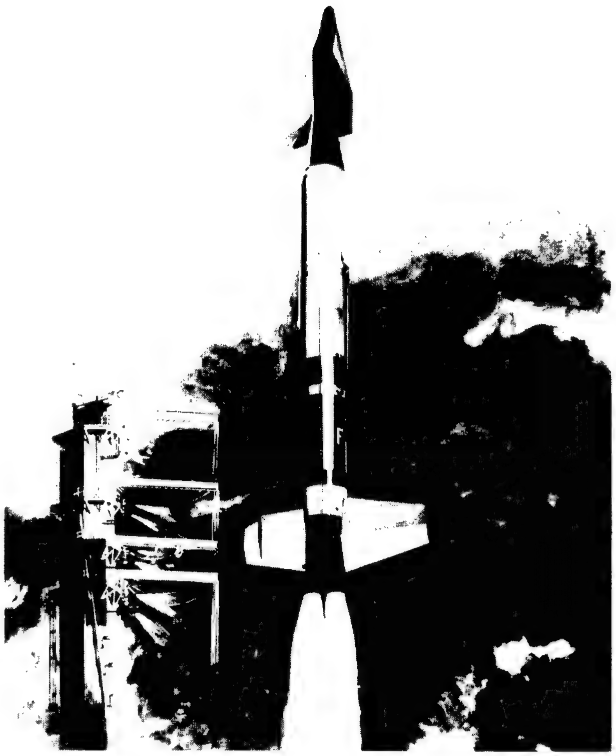
The Lab selected a radiative-cooled slender delta configuration with a flat bottom, a rounded and tilted nose, and twin end plate vertical fins. While research proceeded successfully at Wright-Patterson, the Pentagon and the USAF Scientific Advisory Board gradually lost their enthusiasm for the program. Veterans of Dyna-Soar claim that the necessary support from other agencies was not forthcoming, and that a perceived need to keep up with the Soviets caused a diversion of funds into the Mercury and Gemini programs. Secretary of Defense Robert McNamara cancelled Dyna-Soar in December 1963. Orbital lifting re-entry technology research continued, but was in eclipse until the introduction of the Space Shuttle program. Though Dyna-Soar was never built, the Lab derived valuable research data and technology from the project. Hot structures technology, the



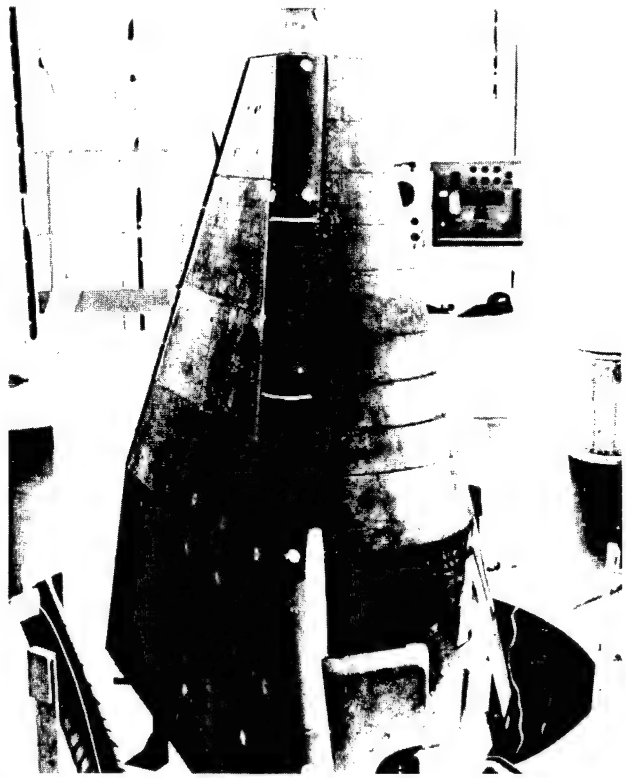
Dyna-Soar mockup, with see-through siding to show its internal arrangements.



Engineer inspecting thermal protection system of the X-20 mockup.



The X-20 was to be launched into space by extra ballistic missile rocket boosters.



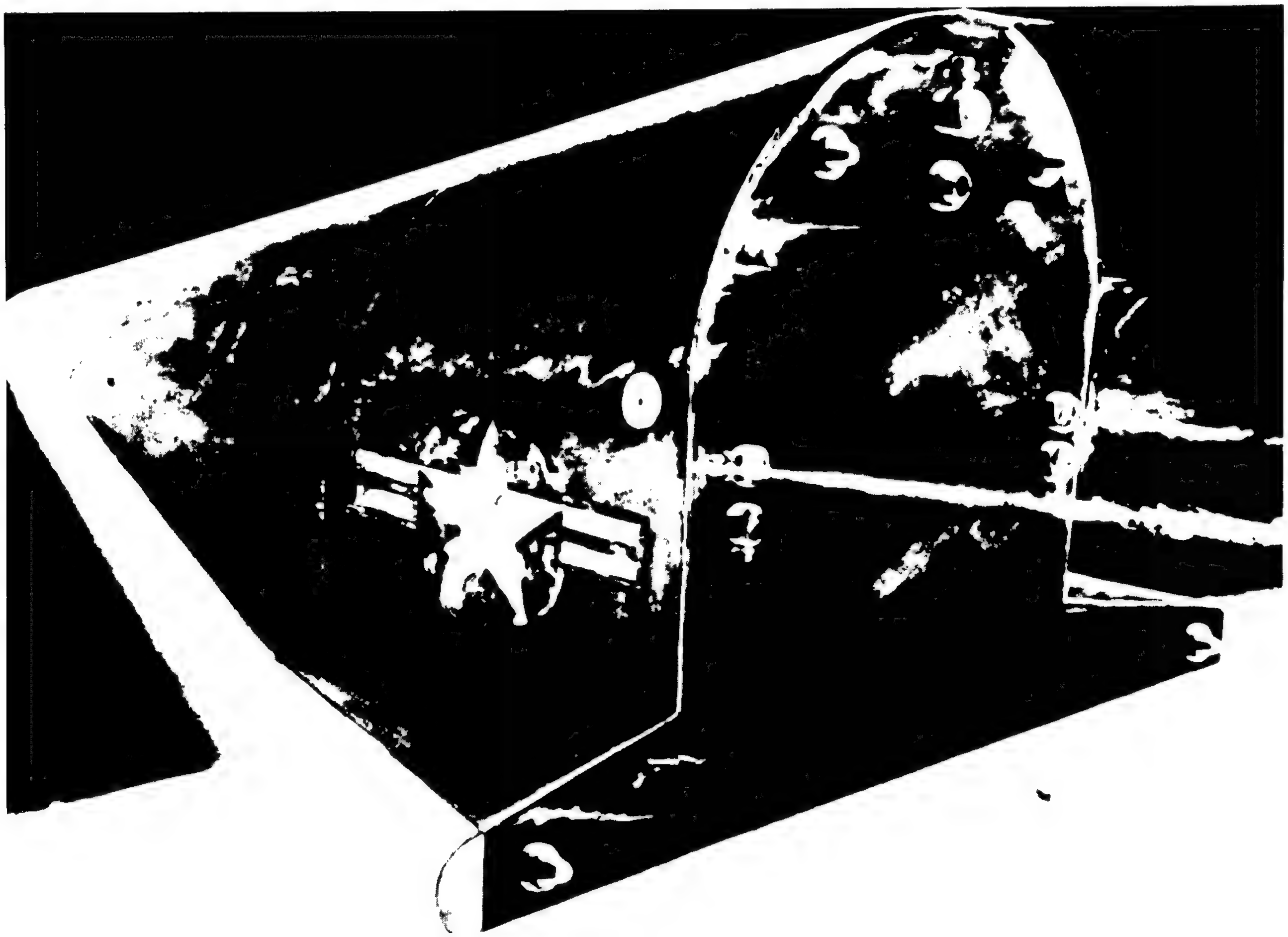
ASSET's thermal protection tiles can be seen in this pre-launch photo. After re-entry the tiles will be scorched and pitted by high-temperature.

aerodynamics of delta re-entry shapes, hypersonic design theory, and other techniques were considerably advanced and provided a base for the Space Shuttle program.

Project ASSET

During the 1960s aerospace research in the United States concentrated on the glamorous and successful Apollo program -- to the detriment of reusable hypersonic boost glide vehicles, although many scientists recognized that the future of space flight lay in that direction. Hypersonic aircraft research was kept alive in the mid-sixties primarily by Project ASSET, which utilized Thor and Thor-Delta boosters to fire glide models down the Eastern Test Range from Cape Canaveral. ASSET was assigned as a project of the newly organized Flight Dynamics Lab. Flight test simulations were conducted in ground facilities, analytical theories and prediction techniques were verified, and structural concepts and materials were evaluated. The ASSET gliders were small flat-bottomed gliders with a 70-degree delta wing (based on FDL's WLB-1 configuration) and a skewed cylindrical body with a sharply tapered nose. Alfred Draper of FDL pioneered the configuration, which differed from Dyna-Soar (then still alive) in several important respects.

The project emerged from several aerodynamic and structural studies conducted at the old FDL beginning in 1959. Testing was delayed due to a lack of available boosters. In July 1962, when it was clear that Dyna-Soar was on its way to extinction, Project ASSET achieved independence as an AFSC-directed Advanced Technology Program. When Great Britain returned a number of Thor missiles in 1962, the necessary test launches became feasible and the first ASSET flight took place in September 1963. The project was managed out of FDL by Charles Cosenza, and support was derived from the Air



Project ASSET was designed to test structural concepts, materials and high-speed aerodynamics.

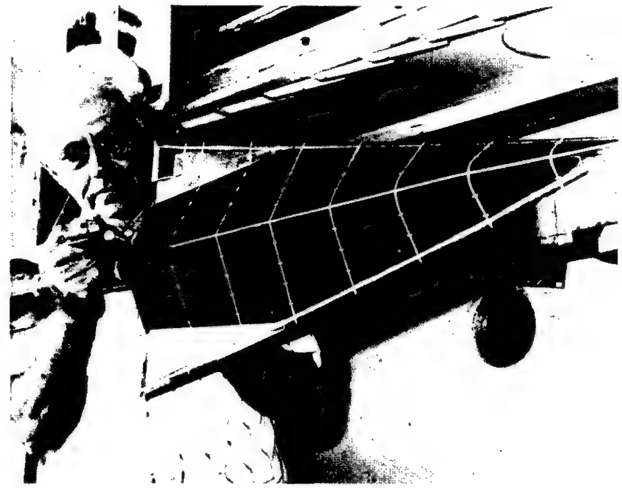
Force Space Systems Division, the 6555th Aerospace Test Wing at Patrick AFB, and the Air Force Missile Test Center. The vehicles were fabricated by McDonnell in St. Louis. Three technical goals were addressed: hypervelocity configuration evaluation; panel flutter and oscillatory pressure data on a trailing edge flap; and investigation of aerodynamic and aerothermodynamic phenomena in low density flow. Each of these problems was suggested by earlier research in the X-15, Dyna-Soar and other programs. The vehicles contained six major subsystems: guidance and control, data sensing, communication and telemetry, tracking, recovery, and range safety self-destruct. Instrumentation -- all contained in a vehicle only 69 inches long, with a wingspan of 55 inches -- was capable of monitoring and measuring an unprecedented range of parameters.

ASSET was a success on all fronts, including cost to the taxpayer, and it laid the foundations for today's Space Shuttle program. Manufacturing and systems technology were considerably advanced, and a number of thorny questions about the hypersonic regime were answered. The results of Project ASSET were published in 1965, making a significant impact on aerospace technology.

ASSET was launched into space by old Thor and Thor-Delta boosters, saving a great deal of money.

During this same period Alfred Draper's team in the Flight Mechanics Division explored development of a maneuverable re-entry vehicle with a high lift-to-drag ratio. Many different configurations were studied, by varying such parameters as aerodynamic heating, weights, and volumetric efficiency (the volume of combustible fuel mixture drawn into the engine). Project ASSET data contributed to the process. The result was the development of sophisticated prediction techniques which have been used extensively by the aerospace community during the past quarter century. In addition, the Flight Mechanics Division led the way in other aspects of hypersonic configuration research.

Lab engineers conducted experiments with Mercury-type capsule configurations before NASA did, and also explored various lifting bodies, airbreathing configurations such as the Scramjet, aero-configured missiles, and

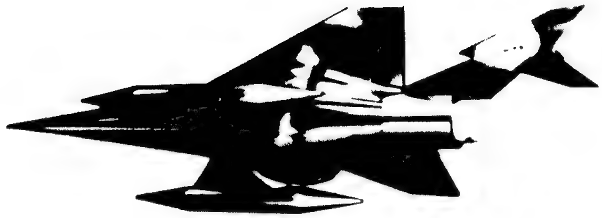


Work on aero configured missiles advanced understanding of high speed flows, and directly influenced many hypersonic vehicles now under study.

advanced launch vehicles such as those eventually used with the shuttle. When NASA formally recommended a Space Transportation System in 1969, the proposal closely followed suggestions already made by FDL engineers. The Lab played a major role in the President's Space Task Group, organized in 1969, influencing the eventual design of the space shuttle.

Throughout the history of hypersonic glide research, FDL engineers have been on the cutting edge. Alfred Draper, Melvin Buck and others have contributed significantly to the work of NATO's Advisory Group for Aerospace Research and Development (AGARD).

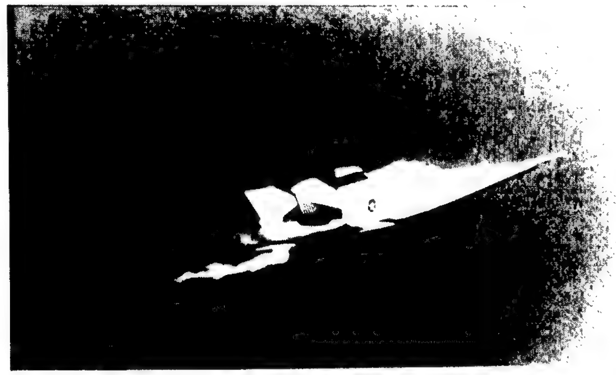
In the late 1980s the space shuttle and the National Aerospace Plane are the most publicized and promising aerospace projects, and they will probably continue to enjoy high priority through the coming decade. Next to NASA itself, no organization has contributed more to space vehicle design than FDL's Aeromechanics Division. In fact, NASA was a prime beneficiary of the Flight Dynamics Lab's research. The Division's aerothermodynamic work (by Richard Neumann and others) made possible the first high lift-to-drag configurations, and also produced



This hypersonic scramjet model explored high speed propulsion concepts long before the National Aerospace Plane was envisioned.

concepts for maneuverable re-entry spacecraft, space transportation systems, recoverable boosters, and new ballistic missiles. The pioneering ASSET and X-24 programs are described elsewhere, but it is important to note that the "space shuttle concept" came out of the pioneering work at FDL. In 1967 the Lab initiated an exploration of the integral launch and re-entry vehicle concept, and reports were published in 1968 and 1969 which became the basis for NASA's space shuttle recommendation. The President's Space Task Group, formed in 1969 to develop the program, included two members from FDL. The Lab is proud of its contributions to the nation's space program.

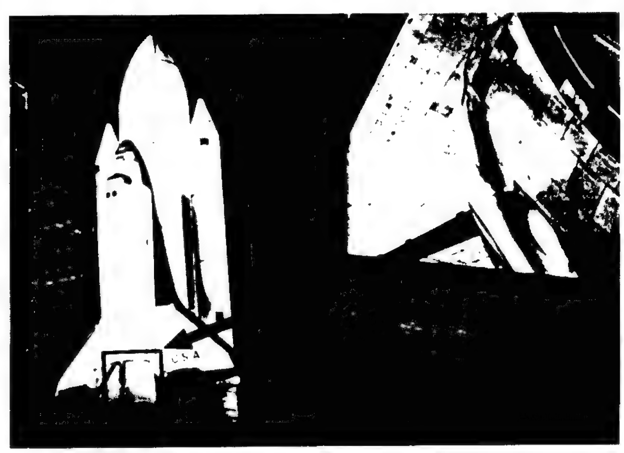
Hypersonic propulsion systems like the one on this aircraft require careful aerodynamic integration with the airframe.



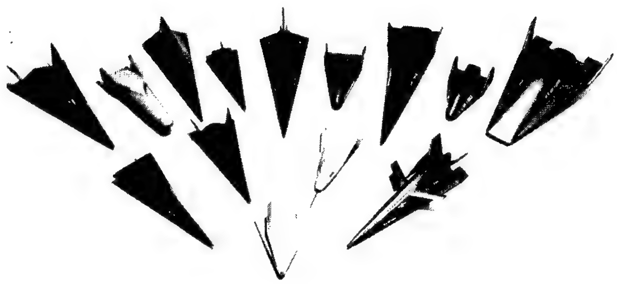
The X-24B used rocket motors for extra speed and range.

During the early seventies FDL engineers participated in the selection and evaluation of thermal protection systems and other aspects of the emerging shuttle design. Some of the actual testing of shuttle components and configuration elements was performed with the X-24B. For example, the detailed approach and landing techniques still used by the shuttle were developed at the Lab. When the first successful shuttle landed at Edwards AFB in 1981, General Marsh -- in a welcoming speech to the astronauts -- referred to this fact. When NASA made public a videotape of the speech, the reference to the X-24B had unfortunately been deleted.

Other FDL projects contributed to the success of the space shuttle, and will impact future

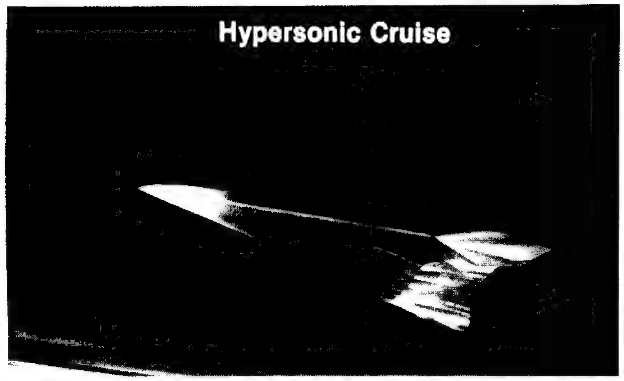


X-24B research helped prevent disaster on the early space shuttle flights.



The Lab has produced many successful high-speed aerodynamically configured designs.

hypersonic vehicles. Project PRIME in the 1960s developed an ablative thermal protection system, and the BGRV made use of this technology. PRIME also demonstrated accurate guidance to the recovery point, cross range maneuvering, vehicle recovery, and weight reduction. Several hypersonic glide vehicles, designated FDL-1, FDL-2, and so forth, were designed during this period, and FDL-5 helped point the way toward a feasible space shuttle



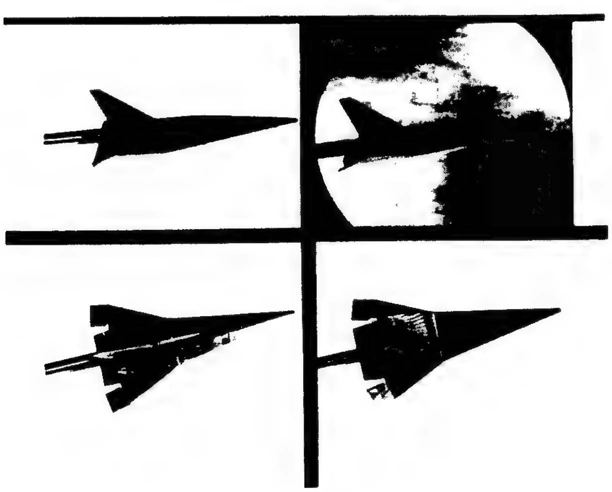
Hypersonic cruise vehicles of the 1990s will use advanced aerothermodynamic concepts developed at FDL.

configuration. FDL-8 was eventually transitioned into the successful X-24B vehicle. Aeromaneuvering orbital transfer vehicles were explored, and a number of unique computer design programs were created. Of particular note is the work of Val Dahlem on the arbitrary body analysis program, which has become a standard throughout industry.

X-24B wind tunnel model, coated with oil. The streaks indicate aerodynamic flow.

The FDL-5, a successful in-house project.

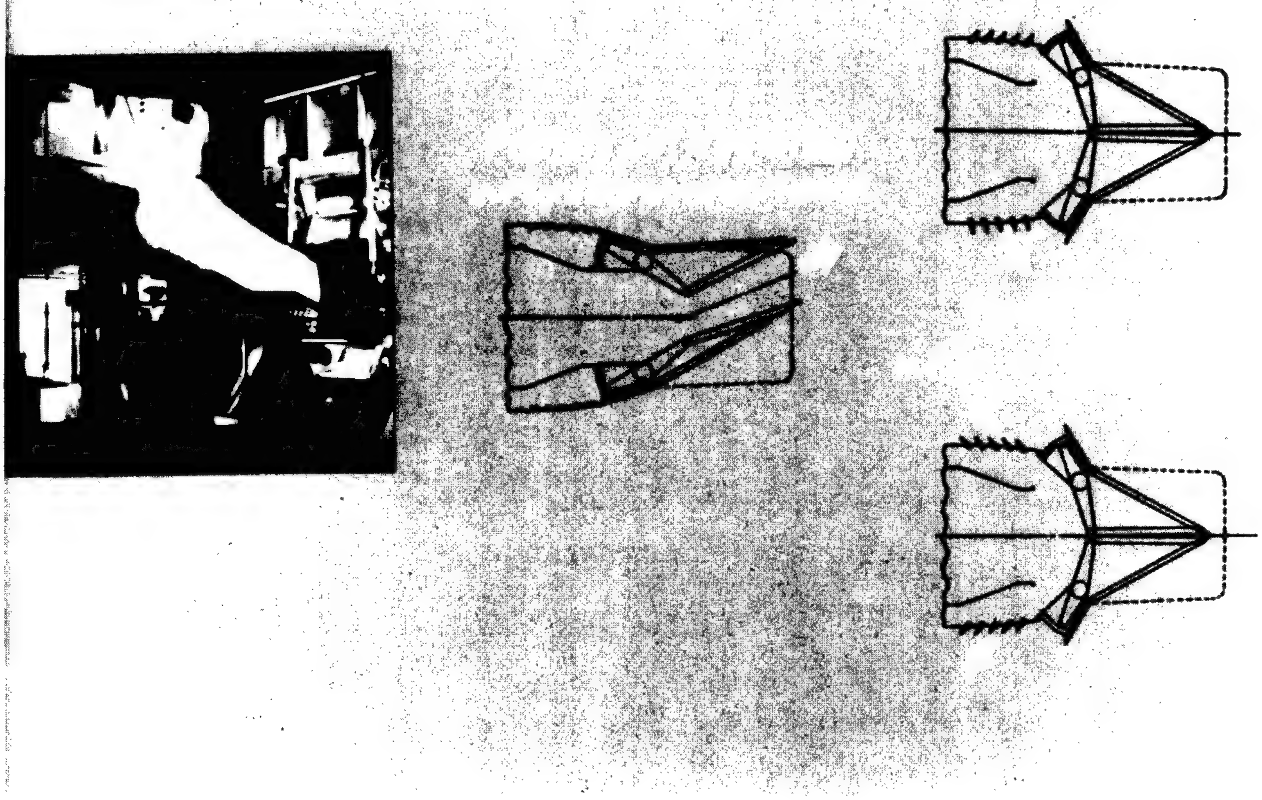
Surface flow patterns and scorching at elevated temperatures on a PRIME model.



Surface flows and shock waves of a typical maneuvering re-entry vehicle.

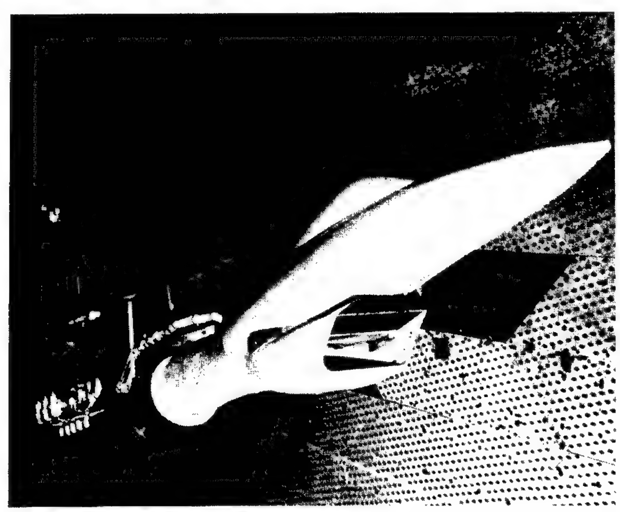
Inlet Design Aerodynamics

Beginning in 1951 the Lab pursued in-house research on inlet design improvement for a variety of weapon systems, including the B-57, B-52, T-38, F-104, F-105, F-106, GAM-87, B-58, RS-70, and F-111. The goal was to improve efficiency at higher Mach numbers and better integration of inlets and airframes. Success was achieved in decreasing buzz, engine surge and stall, and other inlet-related problems. These improvements can be attributed to the breadth and flexibility of the research philosophy adopted from the beginning at Wright Field. The RS-70 inlet system, for example, was developed during 1960-1961. It was one of the most



Schematic showing the primary advantages of the two-dimensional thrust vectoring nozzle over the axisymmetric nozzle.

complex and sophisticated inlets ever designed: a two-dimensional external-internal compression inlet using variable geometry for high performance with minimal boundary layer bleed drag. Because of the inlet's size, special problems of airframe integration had to be overcome, and the testing program was one of the most extensive ever undertaken by the Air Force up to that time. In fact the inlet was not flyable until an automatic inlet control system was designed in the 1970s.



The Project Taylor-Mate inlet integration study influenced the design of many advanced fighters.

Also during the sixties the Lab explored inlet configurations for Mach 8 to Mach 25 scramjet applications, producing a great deal of theoretical knowledge on the physics of high-performance inlet flows. The Propulsion Integration Group,

led by Pete Kutschenreuter, Dick Balent and Keith Richey, demonstrated the use of force balances to measure hypersonic inlet performance. More than twenty years later, this work is making a major contribution to the design of new scramjets and the National Aerospace Plane.

A project demonstrating the influence of highly integrated propulsion streams on aerodynamic performance was completed in the 1980s. This work makes it easier to evaluate advanced aircraft designs having sophisticated inlet and exhaust nozzles without extensive wind tunnel testing.

The Airframe Propulsion System Integration (APSI) program was initiated by the Air Force in the late sixties to develop design criteria for better integration of engine inlets with the airframe. FDL's major roles in the APSI program included Project Tailor-Mate, which led to the development of an inlet for the F-16, which was experiencing stall problems during its development. General Dynamics was the contractor. Eight configurations were designed, then narrowed down to four, which were tested in the wind tunnels at Arnold Engineering Development Center. Steady state and dynamic inlet performance data were obtained, and by 1971 the optimum configuration had been defined: an inlet shielded by locating it under the forebody or wings.

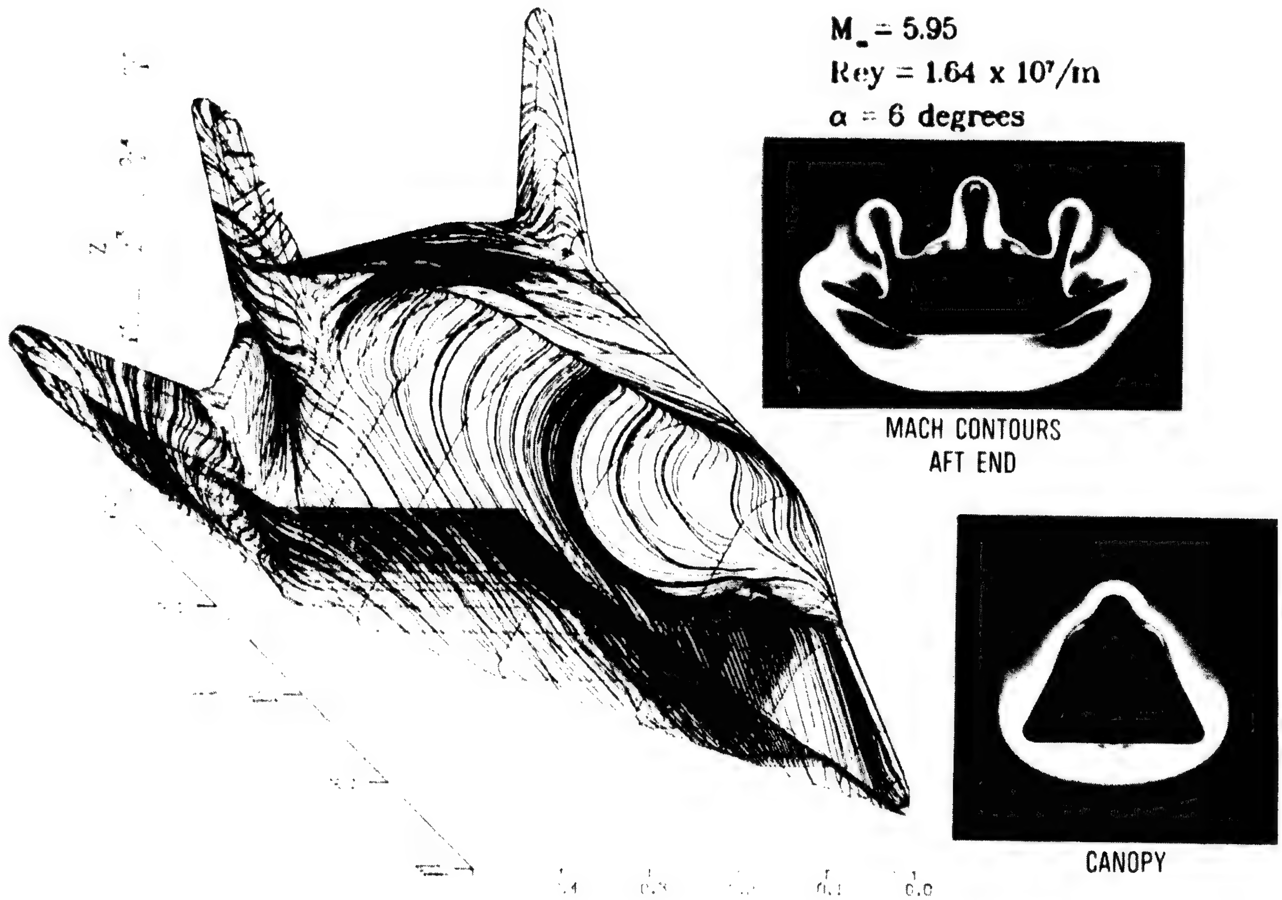
The F-111 aircraft, already in use at that time, was having serious problems with inlet induced compressor stalls -- that is, the engine compressor would shut down because the inlet did not provide enough flow at certain times. Aeromechanics was given the task of isolating and correcting the deficiency. Stall sensitivity was determined with respect to a wide range of flight factors, and the necessary modifications were identified. No major configuration changes in the airframe were required, and flight testing was successful. Stall was virtually eliminated while increasing the maximum speed of the F-111.

The Division also participated in development of an advanced nozzle for the F-15B STOL Maneuvering Technology Demonstrator.

New Advances in Aeromechanics

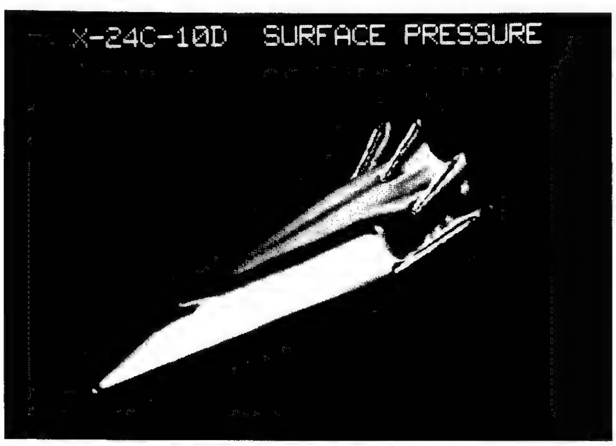
At the time of the 1958 and 1963 reorganizations, aerodynamics technology was the responsibility of the Aeromechanics Division. Aeromechanics has always maintained a strong and capable in-house team working in both basic research and exploratory development. Today this research is accomplished through the High Speed Aeroperformance Branch, which is concerned with technology in the Mach 5 and hypersonic ranges; the Aerodynamics and Airframe Branch, whose efforts are directed toward more conventional aerodynamics including inlets and nozzles; and the Experimental Engineering Branch, responsible for supporting the facilities and test programs. Until 1970 the Flight Vehicle Branch integrated technologies in conceptual vehicles and developed flight demonstration programs.

Significant advances which have come out of these organizations include the Dynamic Data Editing and Computer Program (DYNADEC), which permits use of the hybrid computer to examine significant quantities of dynamic pressure distortion data of advanced inlet configurations. This tool has been applied to almost all airbreathing aircraft and missiles since the early seventies. At the same time, computational fluid dynamics researchers made the first serious attempts to solve the Navier-Stokes equations. When properly understood, these equations can tell engineers all they need to know about the flow field around an aircraft. Research and computational capability progressed with the help of the world's most powerful computer, built by Cray Research; and in 1978, significant solutions were obtained. Today we have the ability to solve complete vehicles, as was done with the X-24C and the F-16.



SURFACE STREAMLINE PATTERN

High powered computational prediction codes can duplicate surface streamline patterns and Mach number contours on this X-24C.



Lab personnel were responsible for the first complete solution of the Navier-Stokes equations using the X-24C.

By 1980 the Navier-Stokes equations had been used to solve the spike-tipped body "buzz" problem, a longstanding aerodynamics mystery. A more recent accomplishment based on the Navier-Stokes research is the Viscous Flow Field computer program, which can accurately compute the viscous flow field over practical three-dimensional shapes at high Mach numbers. The program has been applied to the design of several biconic missile configurations.

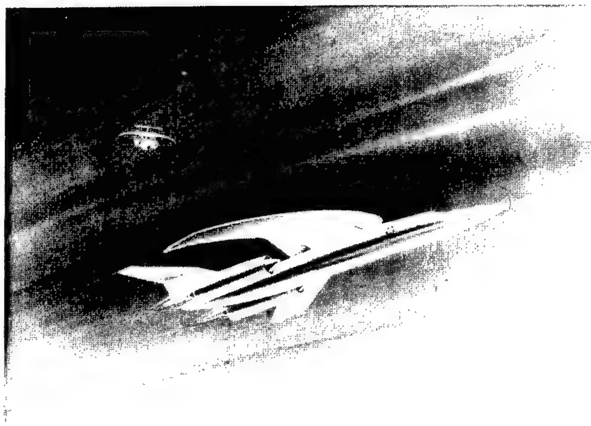
Work also began on the supersonic favorable aerodynamic interference concept. This project, which promised revolutionary changes in aircraft design, involved arranging vehicle components in such a way that interference effects -- previously thought undesirable -- would result in

The parasol wing is one way of utilizing the benefits of favorable interference.

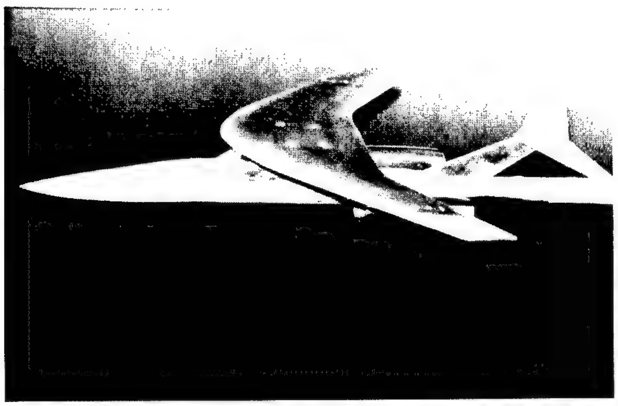
The Advanced Exhaust Nozzle System on the tail end of a wind tunnel model.

increased lift and/or decreased drag. An investigation of the Mach 4 to 6 flight regime was completed and published, and this led to further research on the concept. A "parasol wing" model was fabricated to test the findings in a wind tunnel, and it proved a success. A parasol wing is attached to the aircraft by ties, rather than directly.

In a related project, a KC-135 was outfitted with winglets to reduce drag and improve fuel consumption. Winglets are upturned wing ends or other small airfoils near the wingtip. During the same period, the Cold Gas Ejection Nose Tip was tested to improve missile survivability in adverse weather. Many other tests conducted in the RENT (Re-entry Nose Tip) facility have



Artist's rendering of favorable interference concepts.



Parasol wing, tested extensively for favorable interference effects.

contributed to the development of the U.S. ballistic missile force.

By the early eighties the Lab had completed the Advanced Exhaust Nozzle System Concepts Demonstration Program, suggesting design improvements for a wide range of aircraft. The reduction of aircraft cruise drag, utilizing nozzle thrust vectoring for trim, was one major payoff of this program.

1981 saw the acceptance of an aero-configured missiles project, aimed at optimizing the aerodynamic characteristics of air-launched missiles without sacrificing propulsion, control system or warhead advantages. Aero-configured missiles have small wings or other characteristics of aircraft, rather than the

Schlieren photograph showing shock waves generated by a favorable interference model.

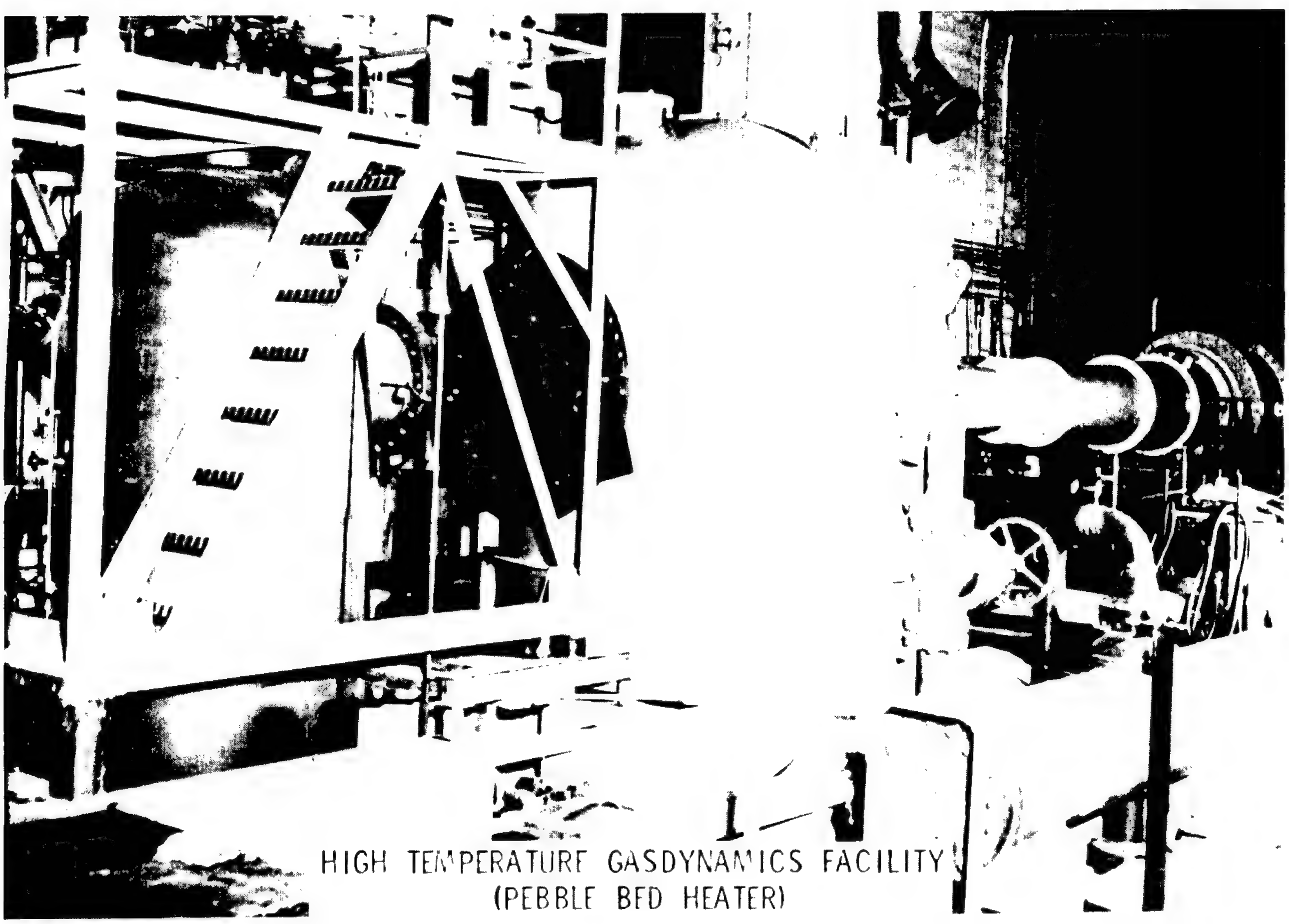
familiar cylinder shape, to improve control and stability.

The sophisticated integration of propulsion components and airframe contours in advanced aircraft presents new problems in aerodynamics. Using a half-span wing design model developed by the Lab's aerodynamic engineers, wind tunnel tests were conducted to determine optimum inlet and exhaust nozzle flows. Work on this and other advanced nozzle concepts has continued into the late 1980s. Recent advances have also been made in supersonic favorable interference technology and on aerodynamic validation of low observable missiles.

The development of hypervelocity vehicles gave a new importance to the fields of gas dynamics and aerothermodynamics. The branch of aerodynamics dealing with the high temperatures generated at high velocities is called aerothermodynamics. In 1958, with the inception of the X-20 Dyna-Soar program, aerothermodynamics research was established as

Advanced exhaust concepts aid in more efficient takeoff and landing, and increase maneuverability and survivability.

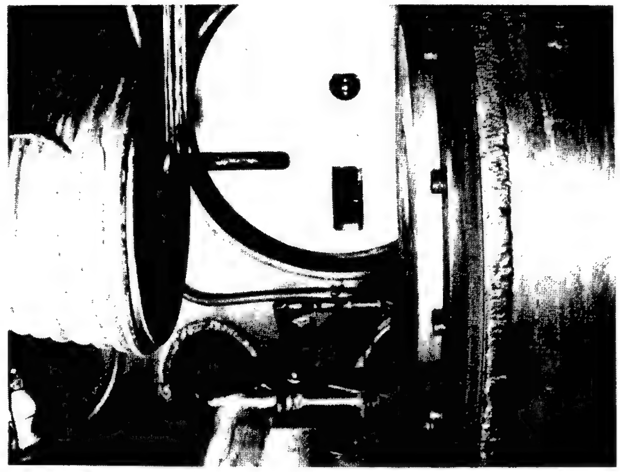
a separate discipline. The first research team at the Lab produced a handbook on aerodynamic heating (WADC-TR-610), and also contributed to the Alpha Draco and Skybolt programs. A number of new techniques, essential for the future of supersonic and hypersonic weapon systems, were created at the Lab. These included a numerical technique for evaluating hypersonic flow fields and studies of hypersonic geometry. Among the projects stemming directly from this work were the Aero-Ballistic Re-Entry System (ABRES) and the aerothermodynamic aspects of the Aerothermodynamic/elastic Structural Systems Environmental Tests (ASSET) program. During the early sixties the Gasdynamic Branch investigated flow field analysis, heat transfer, boundary layer phenomena, ionization and dissociation effects, as well as the effects of



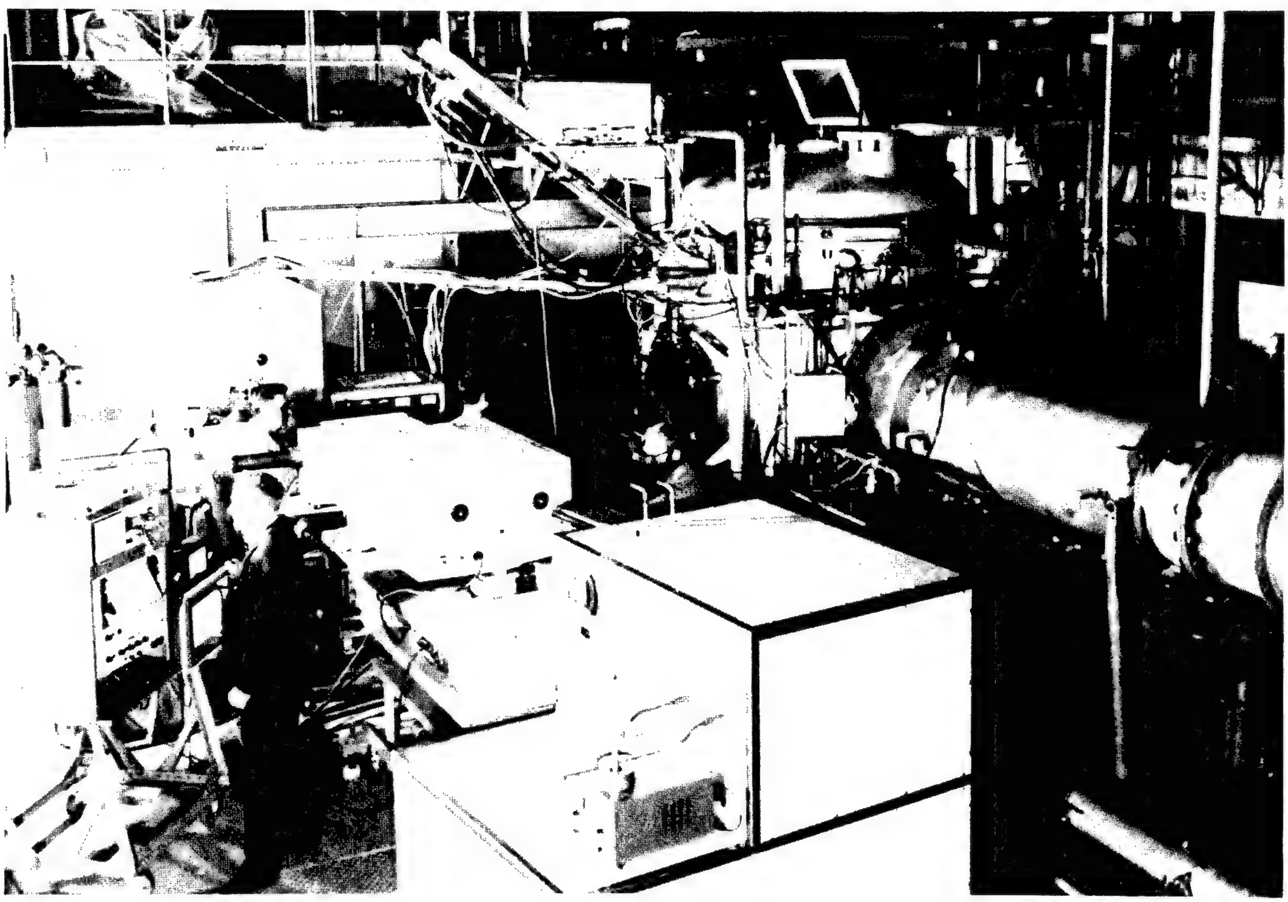
The High Temperature Gasdynamics Facility played a part in many hypersonic aerodynamics breakthroughs.

geometric variables on aerodynamic characteristics. Wind tunnel tests were conducted to establish trade-offs and penalties. The Pebble Bed Heated Facility and the Electrogasdynamic Facility contributed to a number of breakthroughs in the field.

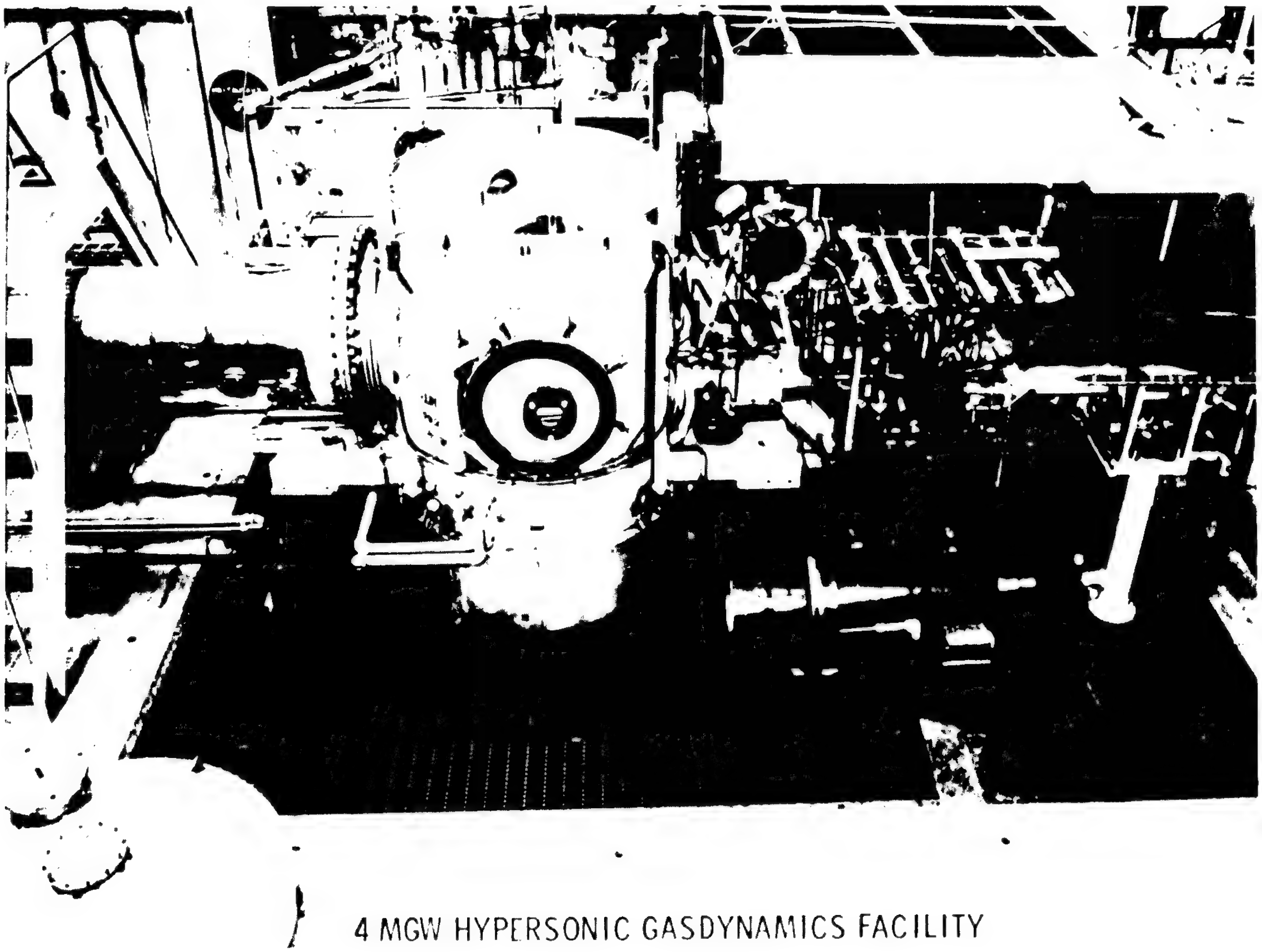
A six-degree-of-freedom computer program was developed which formed the basis of most aerospace trajectory analysis in the sixties, and it is used throughout government and industry today. Any moving body has up to six degrees of freedom, or modes of motion (three angular and three linear); so this program can simulate any possible trajectory. The Lab produced the first three-dimensional characteristics flow field program (used in the Gemini capsule design), and lift-to-drag aerodynamic efficiency was significantly improved. The Re-entry Nose Tip



Sensor probes used to measure properties of wind tunnel flow.



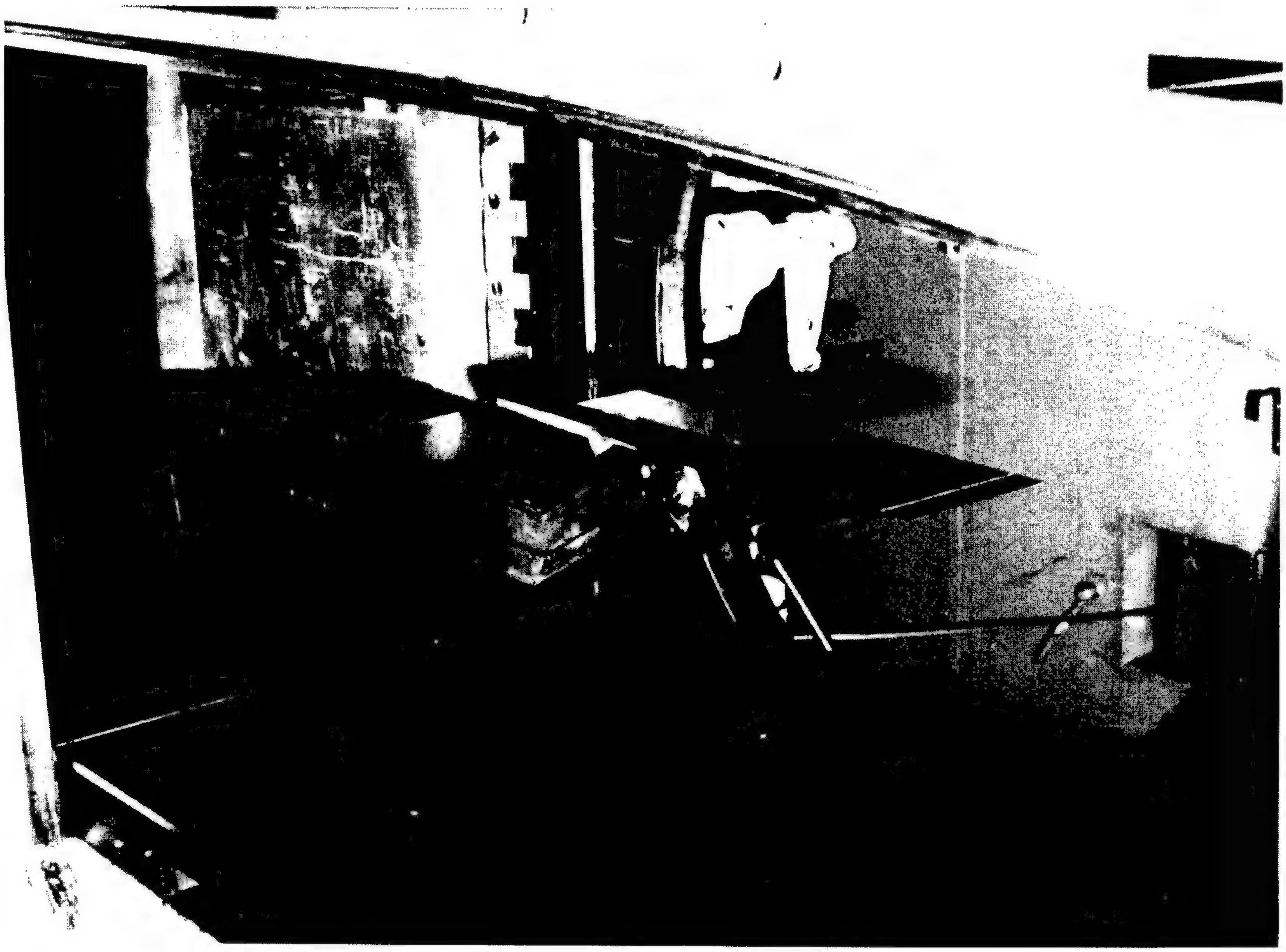
A variety of support and test equipment is required to support a complex wind tunnel like the EGF.



The 4MW Electrogasdynamics Facility (EGF) was built in 1961 to conduct gas chemistry experiments and heat transfer measurements.

(RENT) facility, part of the 50-megawatt test facility has been instrumental in the design of several missiles. It is capable of simulating heating and particle erosion phenomena of ballistic missile reentry. In the early seventies, for example, a number of materials were tested for use in the Minuteman nose tips and forward heat shields. A carbon/carbon weave material proved effective for ablation and boundary layer resistance. The MK 4 reentry body for the Trident C-4 missile was also tested in the RENT facility, which was moved to the Arnold Engineering Development Center in 1979.

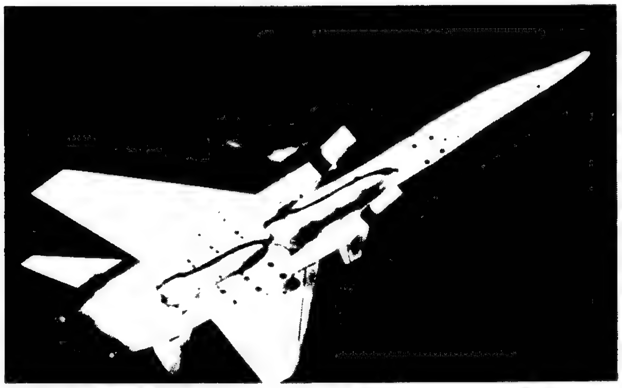
The Aeromechanics Division became involved in the aircraft/weapons integration area in the late 1960s with efforts to establish a consistent data base on the effects of external stores carriage on aircraft performance and stability. External stores are weapons or fuel tanks carried on the wings or body of the aircraft rather than inside. These results were used to develop an empirically based prediction methodology for arbitrary store loadings for both high and low wing tactical aircraft. From this beginning, the activity progressed into study efforts to define carriage schemes to minimize radar cross section, drag penalties and degradation of aircraft stability and control characteristics. Since many of the carriage arrangements resulting from this work placed the stores tangent to the parent aircraft, the separation characteristics of the stores were experimentally investigated to insure safe release. Weapon separation prediction became a subject for



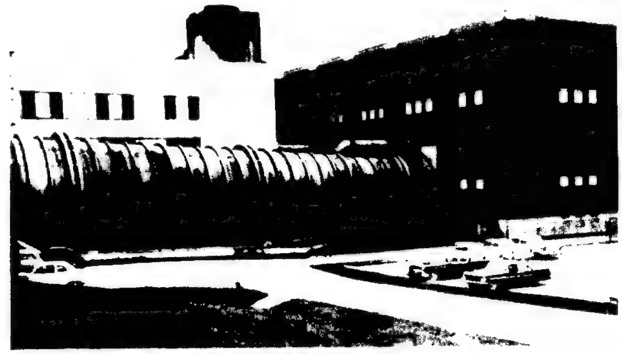
Using weapons bay models like this one, FDL engineers lead the field in research on acoustic and aerodynamics effects from weapons bays and other cavities.

research in the late 1970s and resulted in development of a prediction tool suitable for subsonic, transonic and supersonic speed applications. Refinements to this separation prediction technique, referred to as the Influence Function Method (IFM), are still being made although the method has already been adopted for use by the Navy and by Arnold Engineering Development Center.

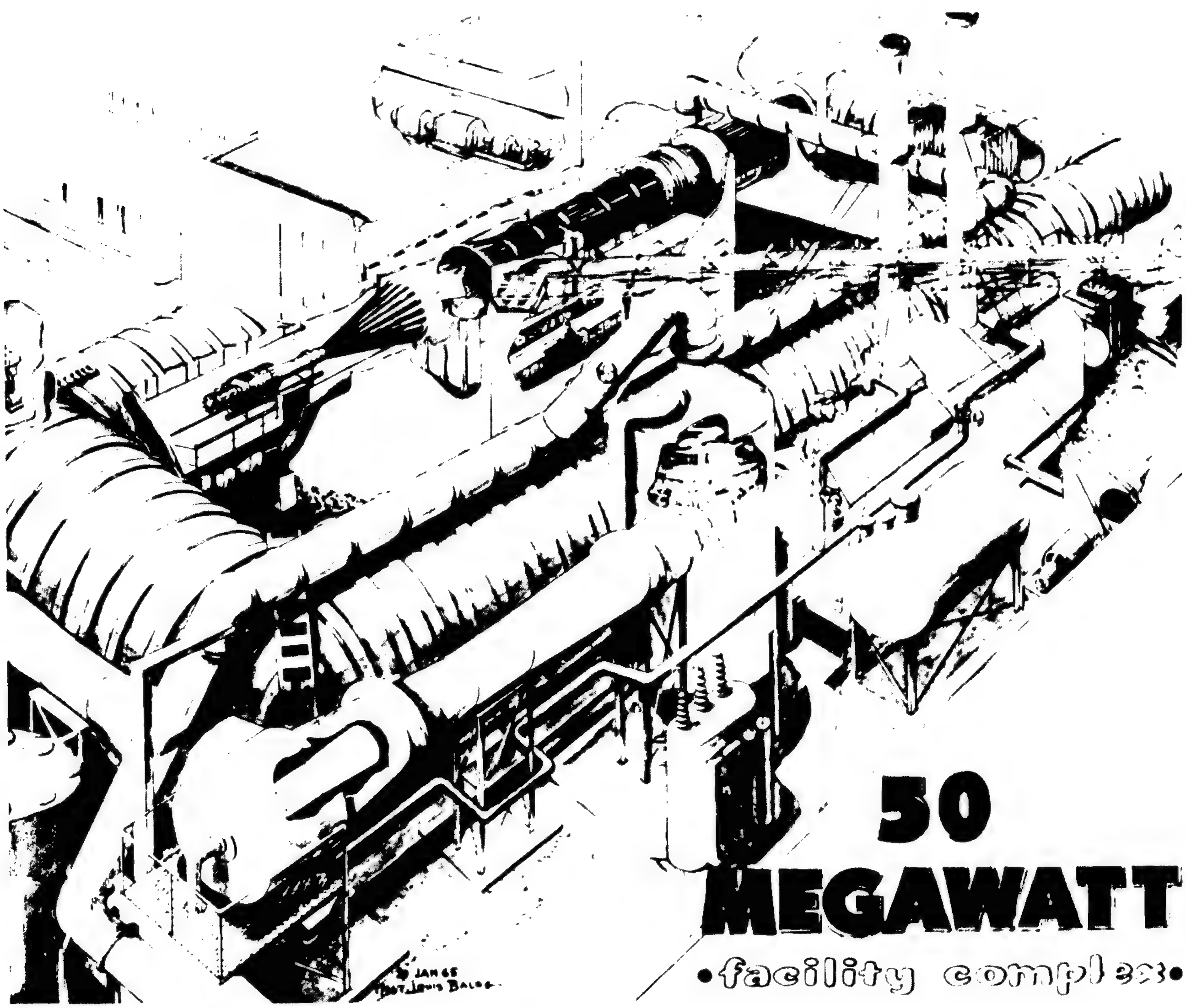
Internal carriage and separation problems have been under investigation since 1973 when means for reducing the severity of the acoustics environment in the F-111 weapons bay was desired to avoid a weapon delivery speed limitation. A weapons bay is a cavity in the aircraft body containing weapons or other components; when it is opened, aerodynamic and acoustic stresses can be created, decreasing the weapon system's efficiency. Subsequent research efforts broadened the speed range and weapon bay geometric parameters data base in attempts to numerically simulate the observed dynamics in a cavity. Questions of scaling relationships between model tests and flight were addressed in a program consisting of testing in the Trisonic Gasdynamics Facility, the AEDC/4T wind tunnel and flight tests of the F-111 aircraft. The scaling question was left unresolved when the project was terminated by structural failure of the instrumented dummy weapon in the F-111 weapon bay. Internal carriage of weapons grows increasingly important as demands for reduced radar cross-section become more dominant in the weapon system design process.



Typical advanced fighter wind tunnel model with low drag conformal weapons attached.



This photo from the 1950s shows the return leg of the 50-megawatt facility coming out of Building 25C.

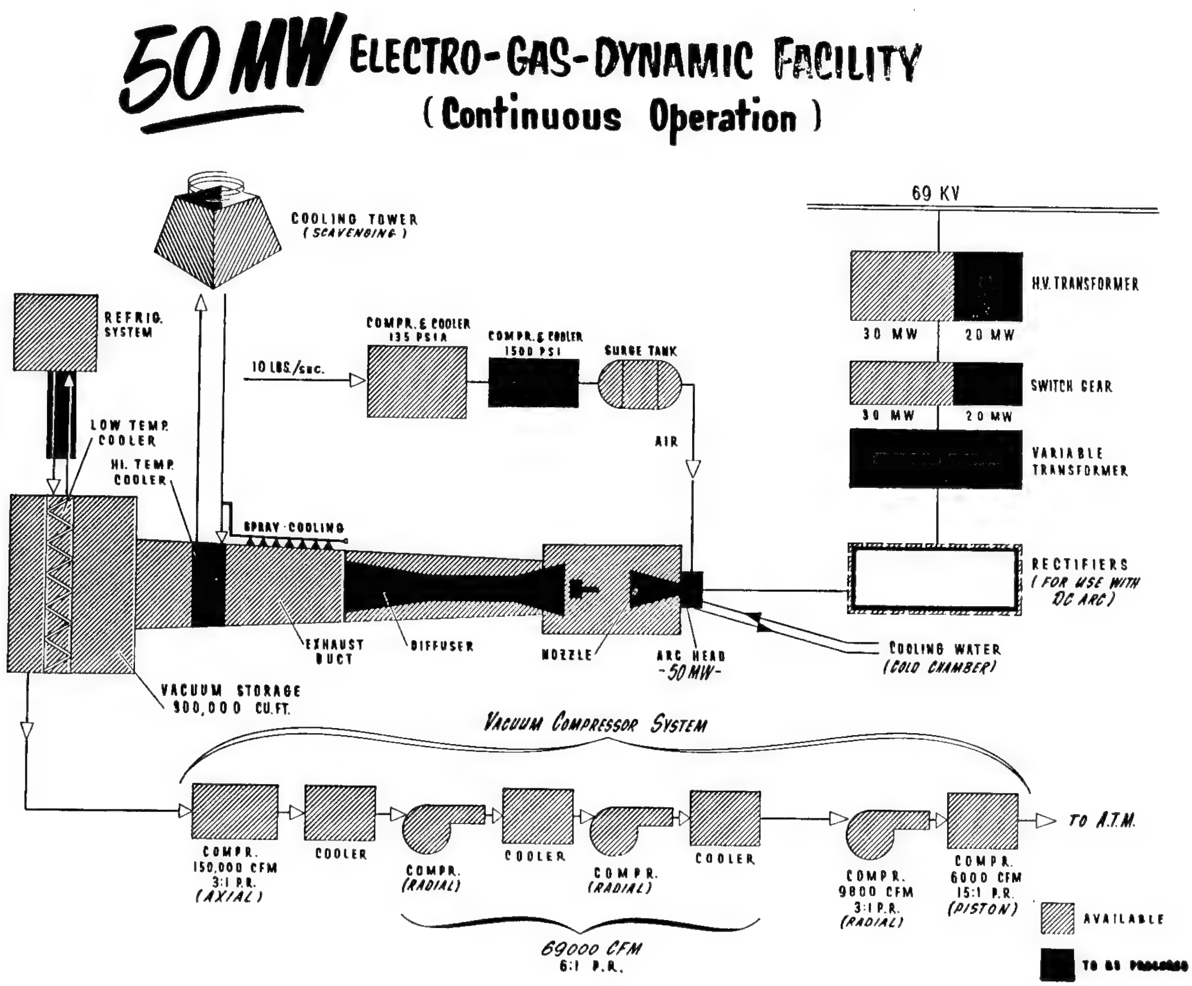


Artist's drawing of internal elements of 50-megawatt facility.

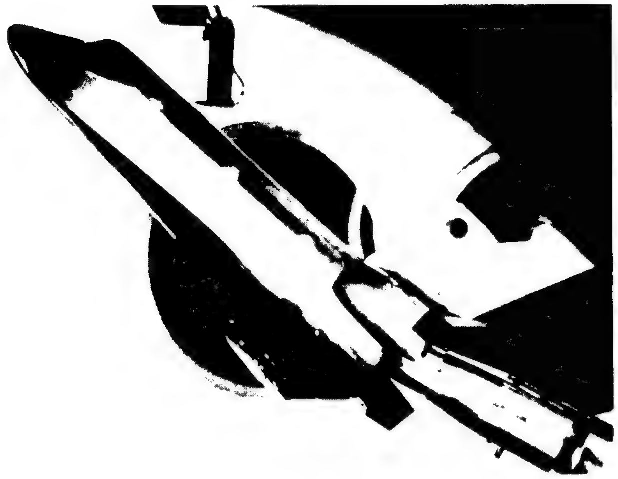
In the eighties the major programs have been the Advanced Weapons Carriage and Separation (AWECS) program, the Cooperative Air-to-Air Technology (CAAT) program, and the Innovative Weapons Carriage (IWC) study program. A CAAT follow-on wind tunnel test program was under way in the late eighties, and plans were being made for continuing efforts into the nineties and beyond. FDL is the leader in the investigation of the aerodynamic and acoustic characteristics of weapon bays.

Expanding research in high speed/high temperature aerodynamics led to the establishment of the Thermomechanics Branch in 1971. The effect of high energy flows on aerodynamic, chemical, material and structural performance was now conducted largely in the 50 Megawatt Test Facility, one of the Air Force's most sophisticated aeromechanics facilities.

Lab thermomechanics expertise contributed significantly to the Space Shuttle development program. Aerothermodynamic engineers in 1979 conducted an independent review of shuttle wind tunnel data, and discovered serious deficiencies in the data base on the orbital maneuvering system (OMS) pods at the lower angles of attack. The Lab then conducted further testing to correct the problem, proving that the shuttle would not survive high cross range missions without additional thermal protection in



Schematic of the 50MW facility.

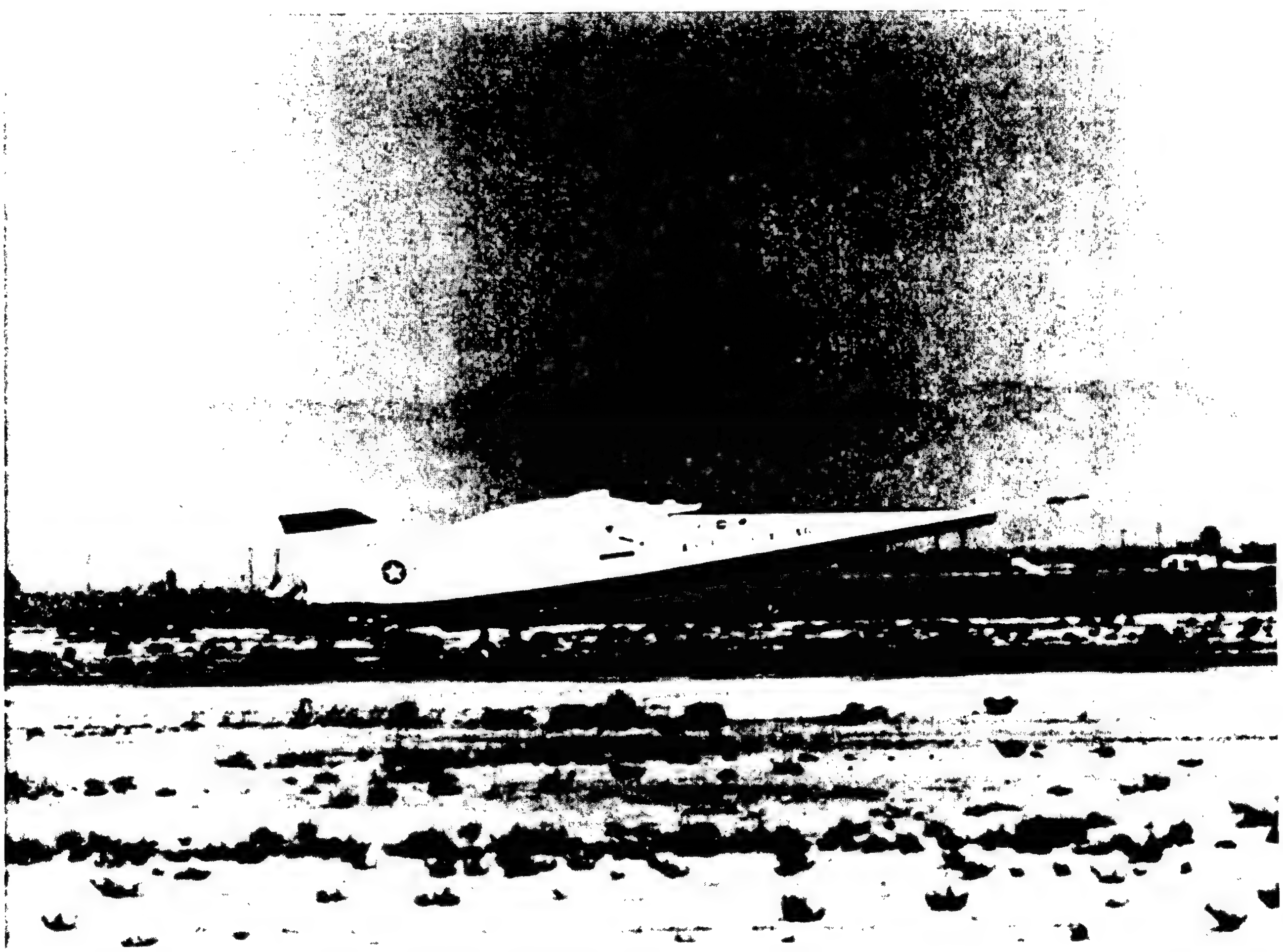


Aeromechanics Division conducted aerodynamics and heating work on this space shuttle wind tunnel model.

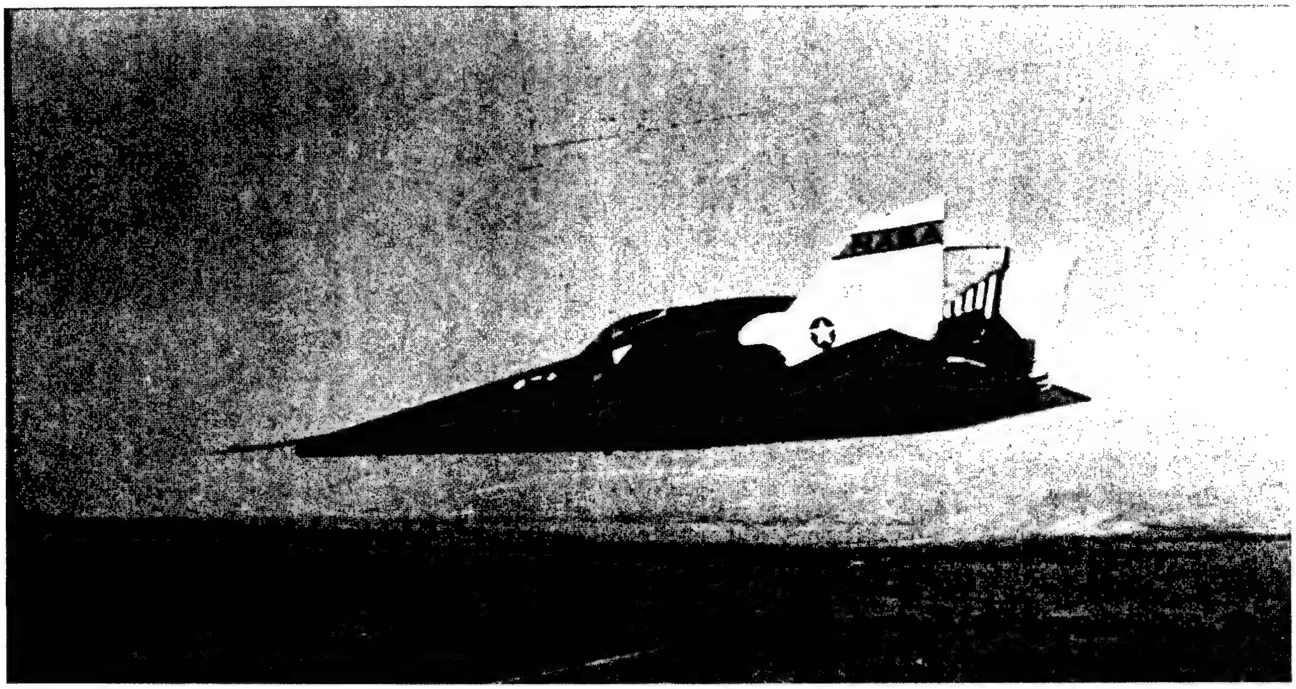
the pod regions. Retrofitting was carried out, thus expanding the shuttle's operating envelope. This and other wind tunnel tests on the space shuttle also resulted in new prediction and analysis techniques which helped reduce the costs of the shuttle program.

As one will notice during reentry and landing, the shuttle approaches the airstrip at a very high angle with the nose up. Had the original reentry and landing approach been used, the shuttle would have been lost.

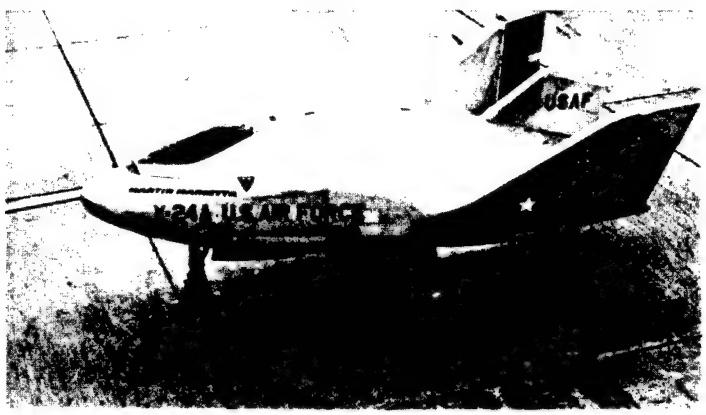
Data gathering, analysis and dissemination has always been a major part of the Aeromechanics Division mission. During the sixties the ASSET (Aerothermodynamic/Elastic-Structural System Environmental Tests) program laid the foundation for much of the later aerospace



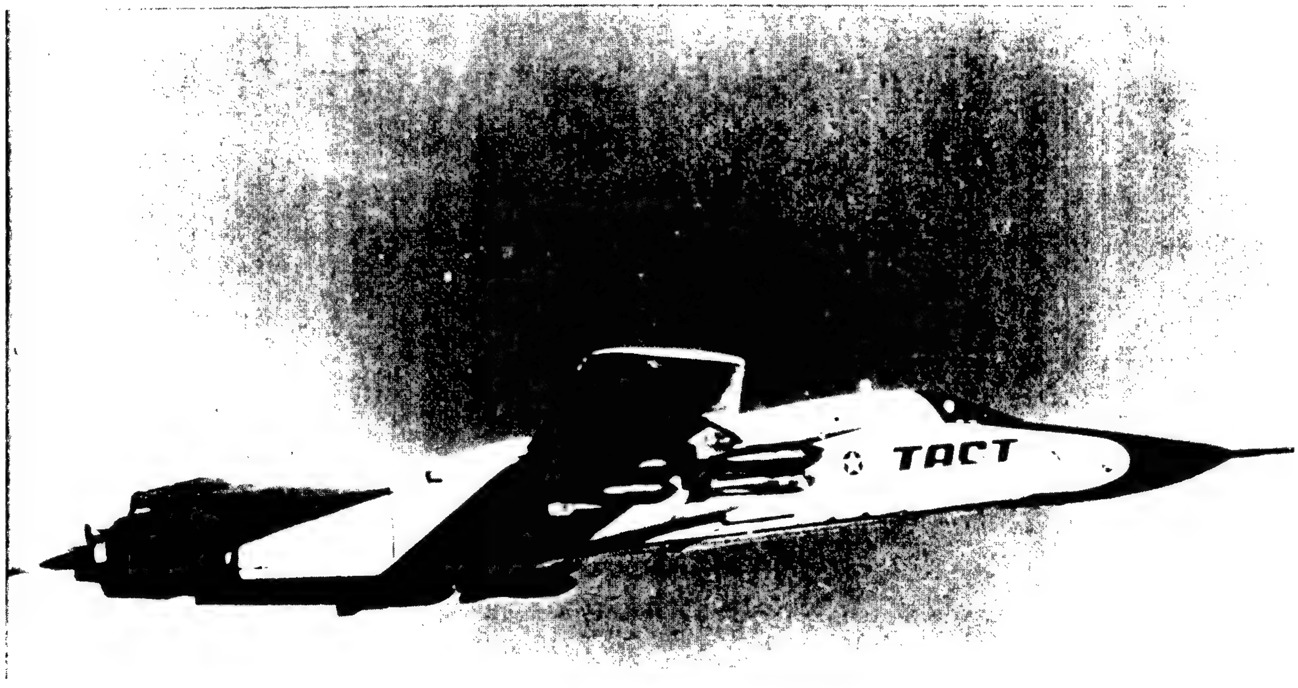
The X-24B returns to Edwards AFB after a successful flight.



Landing approach studies on the X-24B helped develop a safe landing corridor for the space shuttle.



X-24A (top) and X-24B (bottom), two major successes of the Flight Dynamics Lab.



The TACT program culminated in a flight test of a wing designed for peak efficiency at transonic speeds.

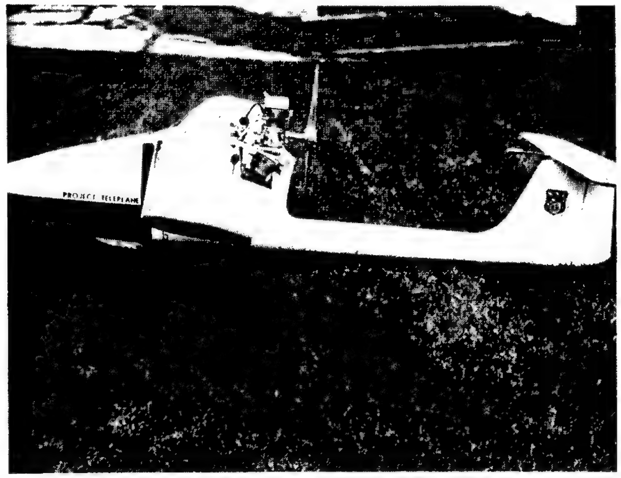
F-111 wind tunnel model, with improved wing design which aided research on the transonic regime.

planning. The division was responsible for the technical direction of such experimental programs as the X-24A PILOT, the Atmospheric Research System, and the Transonic Aircraft Technology (TACT) programs, and later the X-24B.

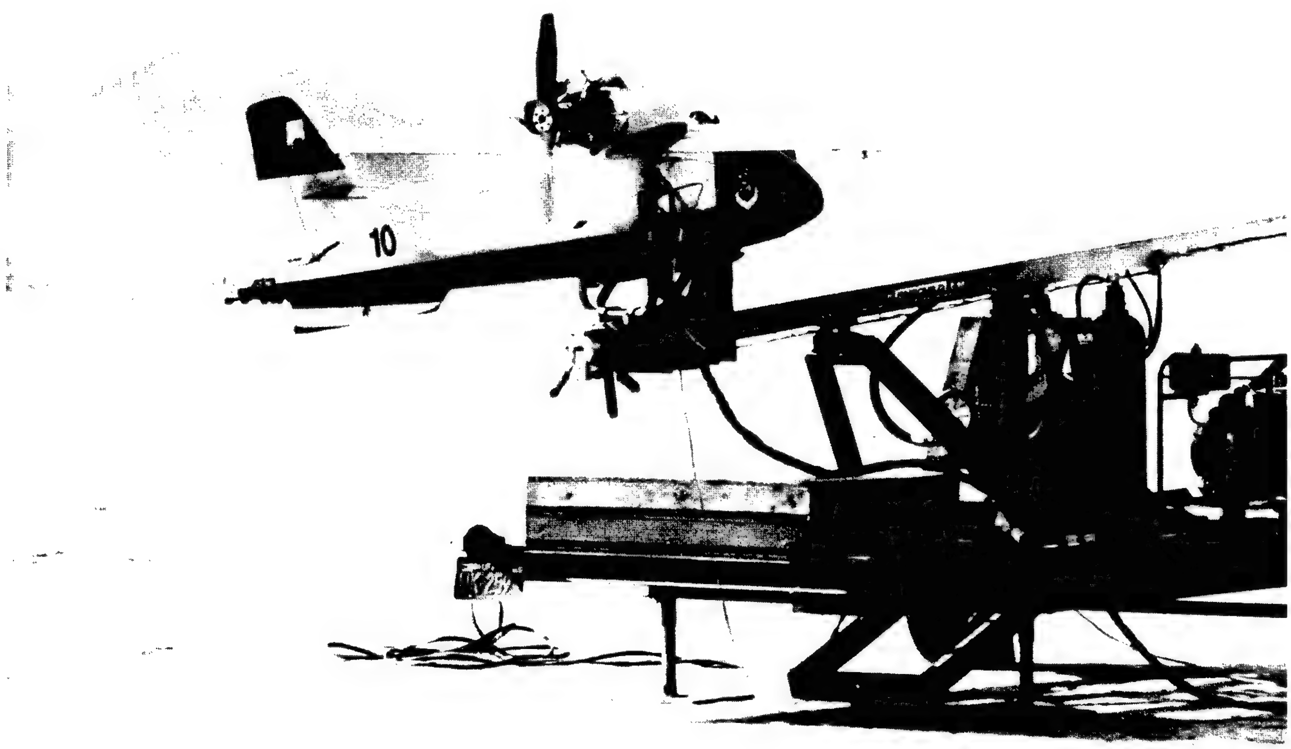
Work began on a new generation of highly maneuverable, multi-mission tactical Remotely Piloted Vehicles (RPVs).

The Teleplane Project Office, established at FDL in 1972, conducted flight testing of subscale radio controlled aircraft in order to establish criteria for RPVs. It developed the low-cost, expendable XBQM-106, a remotely piloted aircraft used in reconnaissance and to attack ground and air targets such as tanks and transports. For a time RPVs were flight tested at Wright-Patterson, until one crashed on Airway Road!

The Aeromechanics Division has also continued to explore advanced aero-configured missile designs. The climb and cruise segments of the flight path are particularly sensitive to aerodynamic considerations, and improvements have been made in lift/drag ratio, zero-lift drag, and the lift curve slope. This technology is expected to improve mission performance of air-launched missiles in both tactical and strategic applications.



XBQM-106 remotely piloted vehicle (RPV).

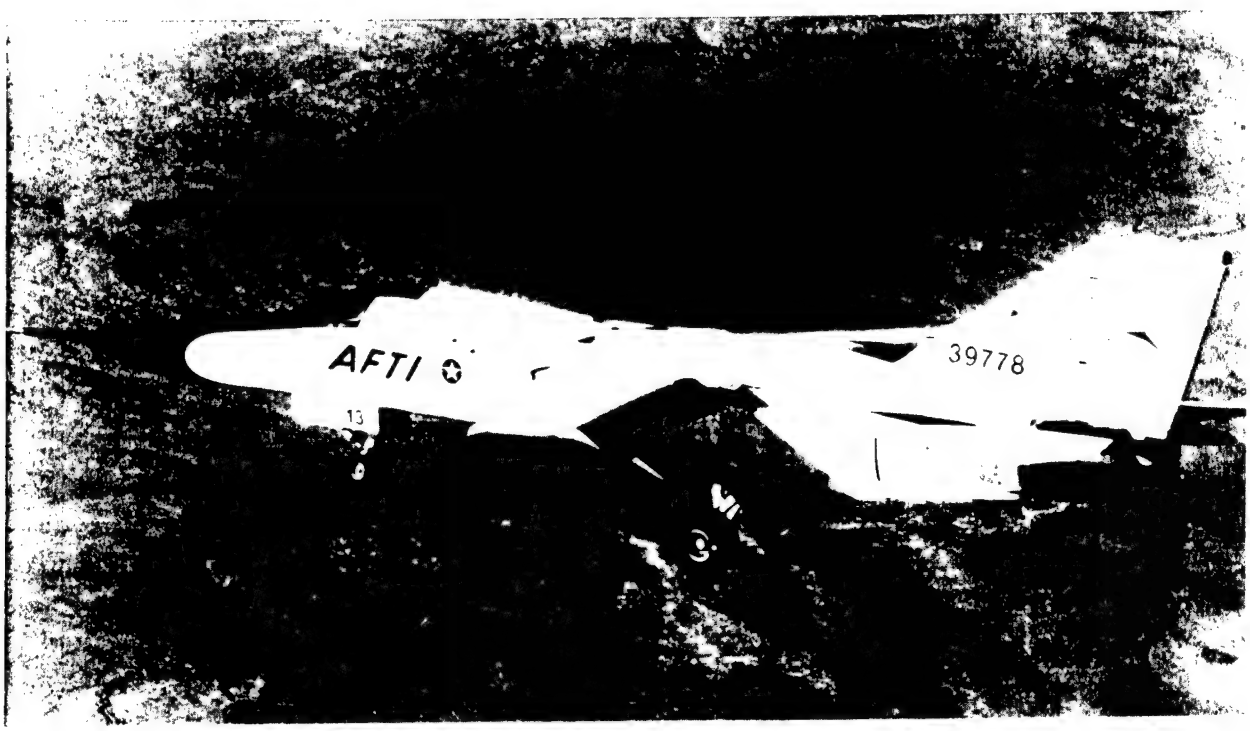


XBQM-106 being launched by a mobile catapult system.

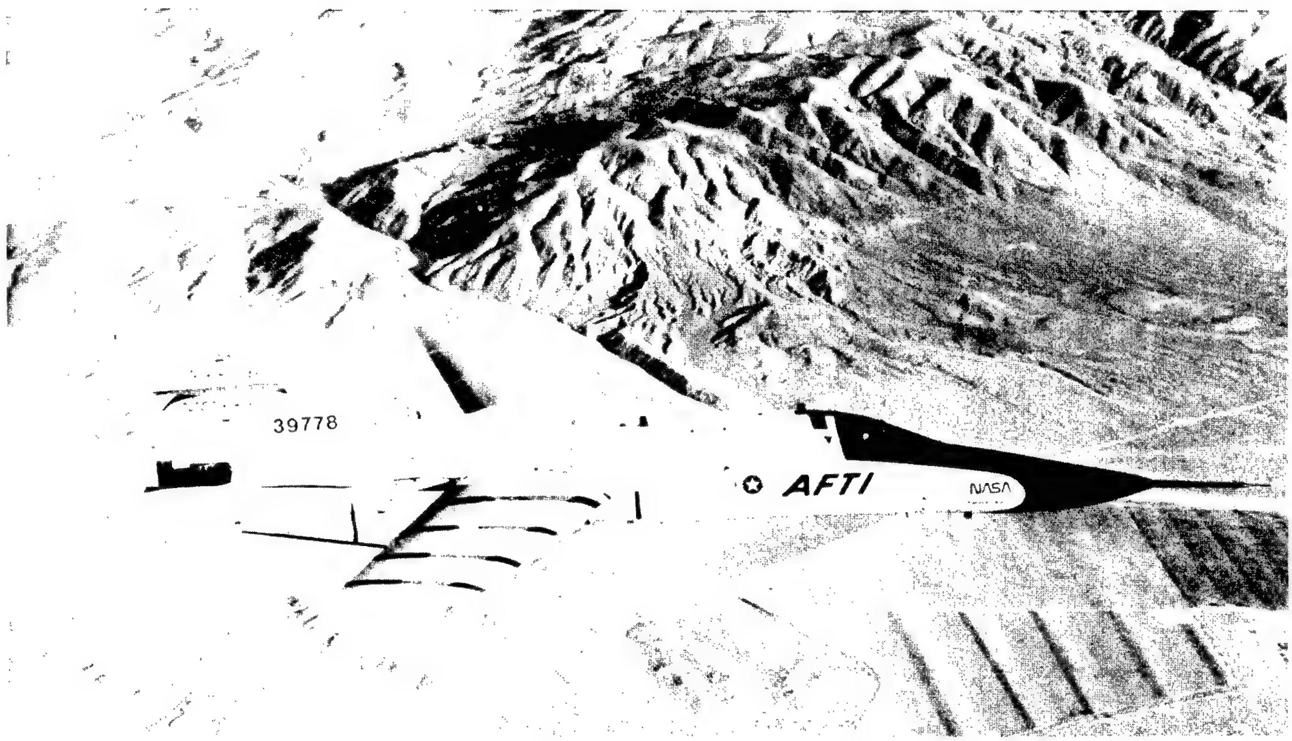
Some Current Advanced Development Programs: the Mission Adaptive Wing

Advanced Fighter Technology Integration was also applied to the development of new wing concepts, beginning in 1975. Using an NF-111 research aircraft, the FDL Aeromechanics Division and NASA in the late 1970s launched an effort to design a wing capable of adjusting its shape for various flight conditions. The variable camber Mission Adaptive Wing (MAW) has smooth, flexible leading and trailing edges. In the past camber could be varied only by means of flaps, which produce sharp breaks or gaps in the upper surface and increase drag. Thus a standard wing reaches peak efficiency only at a particular altitude, velocity and weight. Subsonic, transonic and supersonic regimes all require different wing shapes for optimum efficiency. The F-111 wing concept was a one-piece leading edge smooth variable camber flap and three independent trailing edge smooth variable camber flaps replacing the standard leading edge

Many hours of wind tunnel testing were conducted on the Mission Adaptive Wing.



Mission Adaptive Wing in its landing configuration. Note how the leading and trailing edges are "bent" down.



The MAW utilized a smooth variable camber version of the TACT airfoil and planform and provided a wealth of wind tunnel test data.

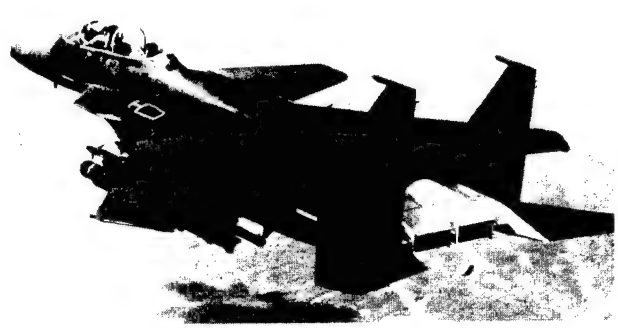
Krueger and trailing edge slotted Fowler flaps. The MAW is controlled either automatically or manually by the pilot; a digital flight control system changes the shape of the wing as a function of pilot inputs, flight conditions and structural loads. Thus the wing can assume optimum camber under any conditions. Phase I, completed in 1986, tested manual controls and verified wind tunnel data. Automatic mode testing was completed in 1988.

Moderate STOL

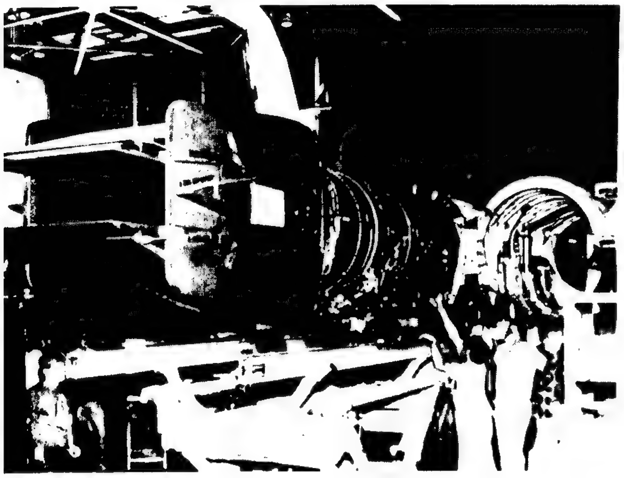
The design of moderate STOL fighters continued to be a major concern of the 1980s. The term "moderate STOL" denotes lift-off and touchdown speeds greater than the minimum required for control by aerodynamic means, without augmented controls. The Division pursued several goals: low observables, advanced wing design, thrust vectoring/reversing, and advanced concepts in weapon and propulsion system integration. Progress was made in improving turn capability at transonic speeds and other maneuverability parameters. Aircraft/weapon integration and separation has also been explored since the 1960s for a variety of aircraft.

STOL/Maneuvering Technology Demonstrator (STOL/MTD)

Research in Aeromechanics and other divisions on two-dimensional nozzles with thrust vectoring capability has been combined with the

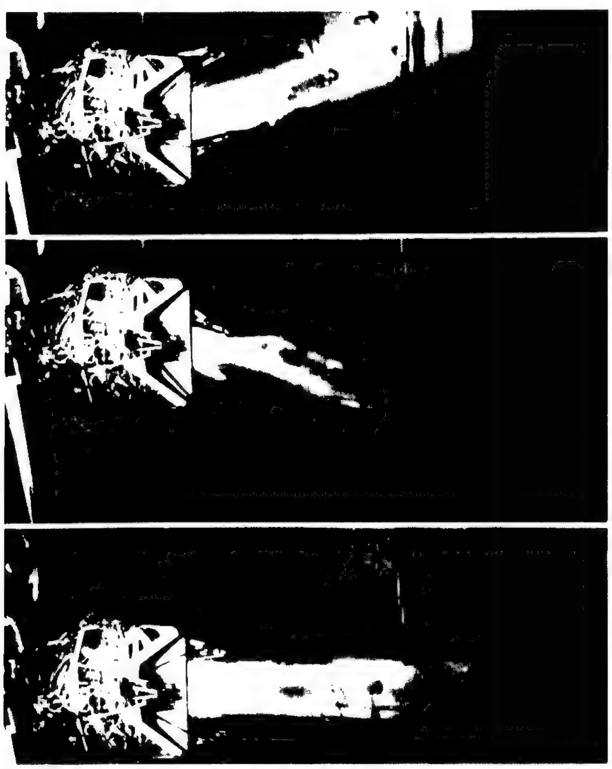


Two-dimensional thrust vectoring nozzles on an F-15 SMTD.



Engine and nozzle mockup being fitted to the F-15 SMTD aircraft for testing.

Air Force's need to land on bomb-damaged runways, producing the STOL/MTD program. In 1980-81 preliminary investigations concluded that such a program was feasible and significant payoffs were possible. McDonnell Aircraft was awarded a contract to modify an F-15 to demonstrate two-dimensional thrust vectoring/reversing nozzles, integrated flight/propulsion control, and all-weather autonomous cockpit displays. STOL/MTD continues under development at FDL. Pratt & Whitney subcontracted to develop the two-dimensional nozzles, the first of which began sea-level ground testing in February 1988. The test program was completed in May and the nozzle was sent to NASA/Lewis in June, where it was installed in the altitude test facility. Between July and October the nozzle was tested for over a hundred hours. The first flight of the STOL/MTD F-15 with standard engines occurred on September 7, 1988. At this writing all of the installed technologies were performing satisfactorily, and the pilots are favorably impressed with the aircraft.



Max up, max down and no-deflection position of the F-15 SMTD thrust vectoring nozzles.

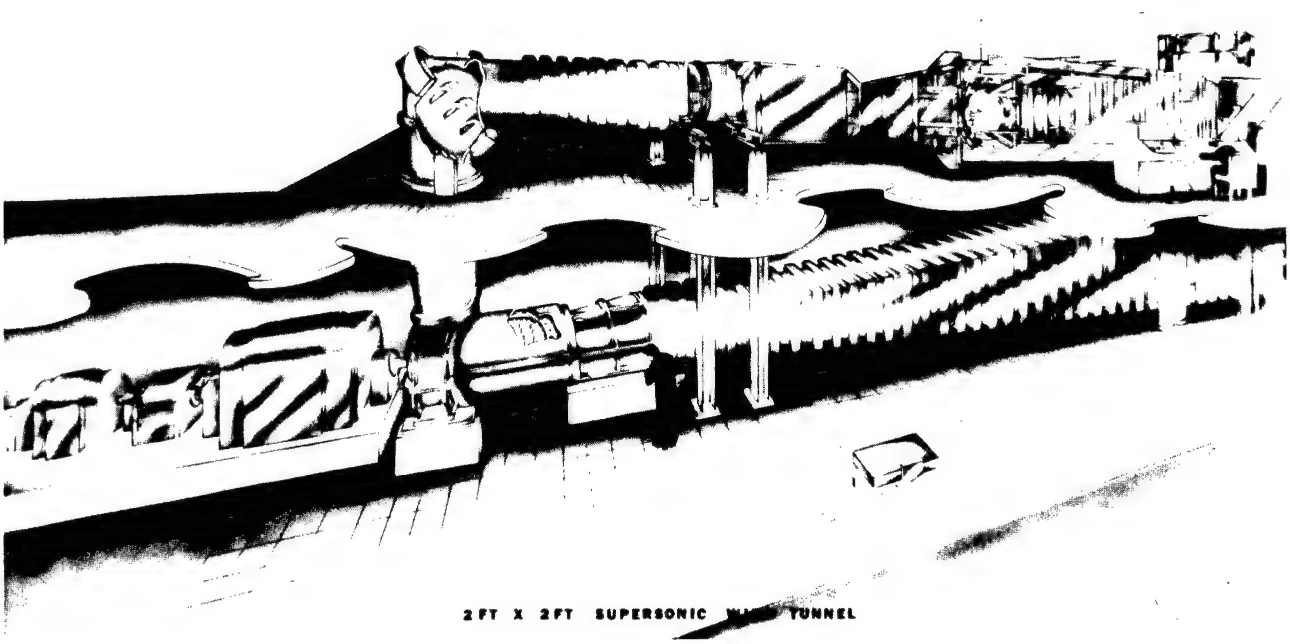
Air Combat Correlation Analysis

Sophisticated computer programs continue to be major products of the Division. In the early eighties the High Speed Aero Performance Branch developed Multiple Tactical Aircraft Performance Evaluation (MULTAC), which is capable of simulating a large-scale stochastic differential air combat encounter (that is, one including random and unpredictable maneuvers) between two opposing forces involving up to twenty aircraft. This analysis demonstrated that the use of one-on-one exchange ratios to predict the outcome of such encounters is inappropriate, due to the stochastic effects. The exchange ratio was shown to be a function of force size and force size ratio. The MULTAC concept has improved air-to-air analysis capability, and contributed to the air superiority and intercept effectiveness of future fighter aircraft.

Current Facilities

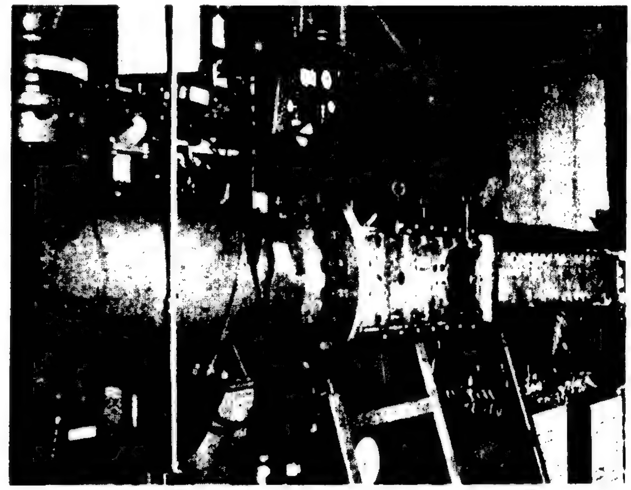
Today, six major research facilities provide most of the test support for the Lab's aeromechanics research. The Philip P. Antonatos Subsonic Aerodynamic Research Laboratory, guided by Melvin Buck, will provide maximum

Laser test in the 2-foot Transonic Gasdynamics Facility.

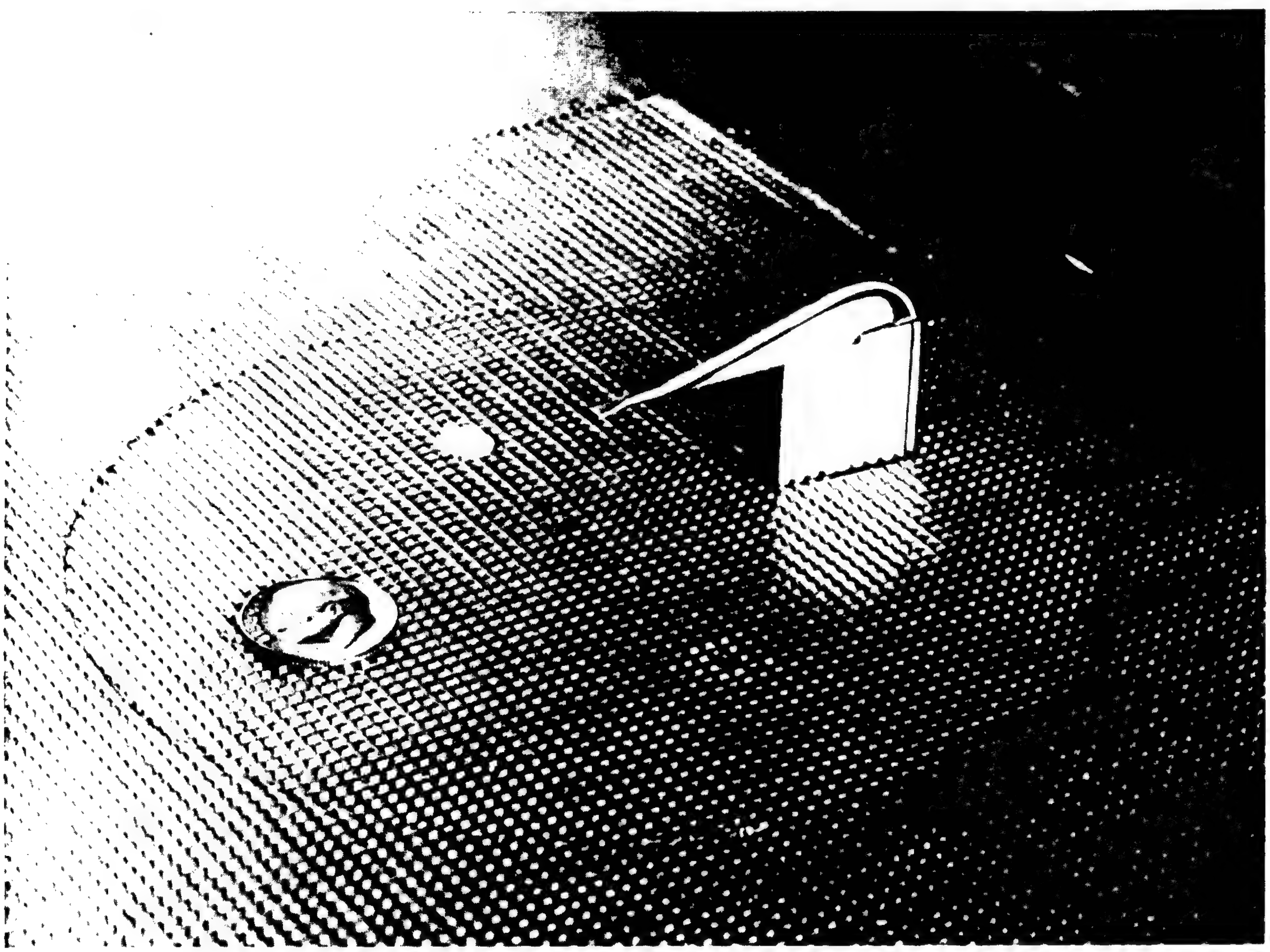


Early drawing of what is now the Trisonic Gasdynamics Facility, showing that this tunnel is of the closed-loop variety. Note the return passage under the main floor.

Engineers can run and monitor all functions of the Trisonic Gasdynamics Facility from this control room.



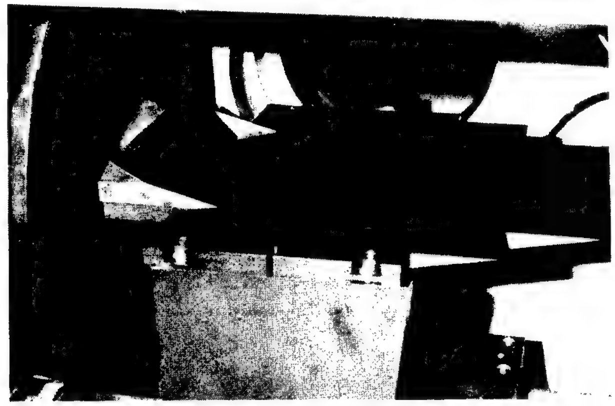
The Mach 3 High Reynolds Number Facility, used for basic and exploratory research.



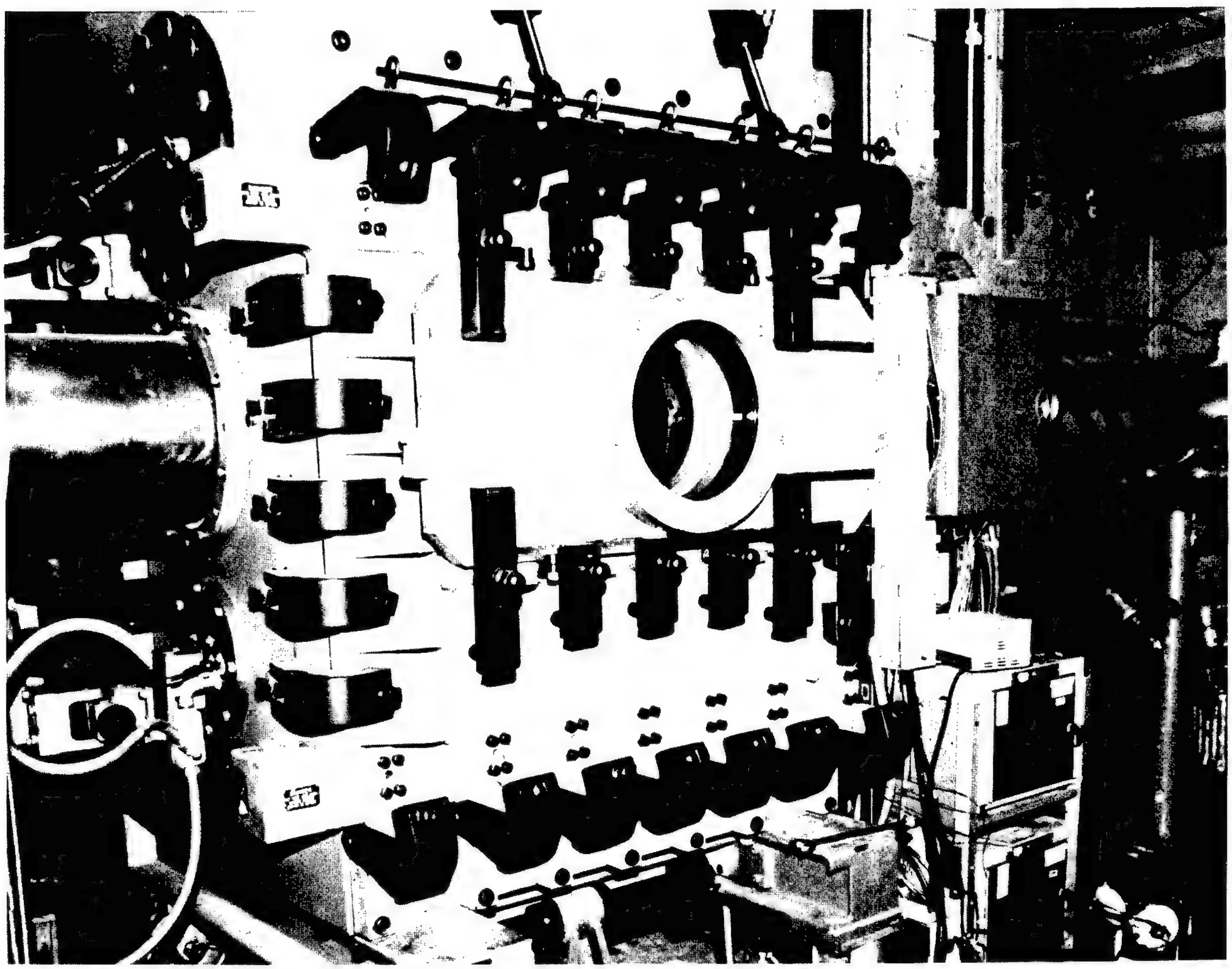
A basic research test in the Mach 3 tunnel, exploring the effects of surface roughness on boundary layers.

flow visualization in an open-circuit subsonic wind tunnel, and is in the process of adding a conventional model support system. The two-foot Trisonic Gasdynamics Facility can operate through a Mach number range of 0.23 to 3.0.

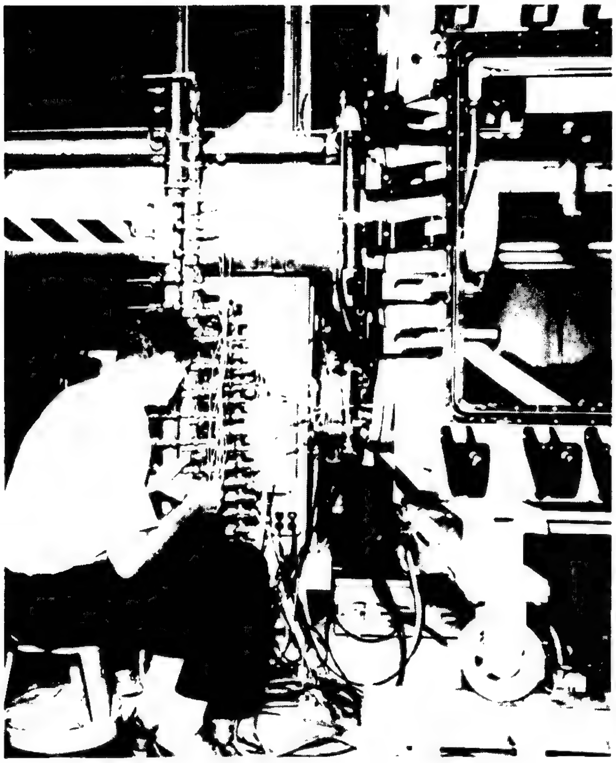
The Mach 3 High Reynolds Number Facility (built in 1968) is an intermittent, blowdown wind tunnel with a two-dimensional nozzle producing a uniform Mach 3 flow. Test models can be strut- or wall-mounted; a 45-channel pressure measuring system and a 30-channel thermocouple reference junction system facilitate data collection.



Smooth flat plate model used for basic research in the Mach 6 facility.



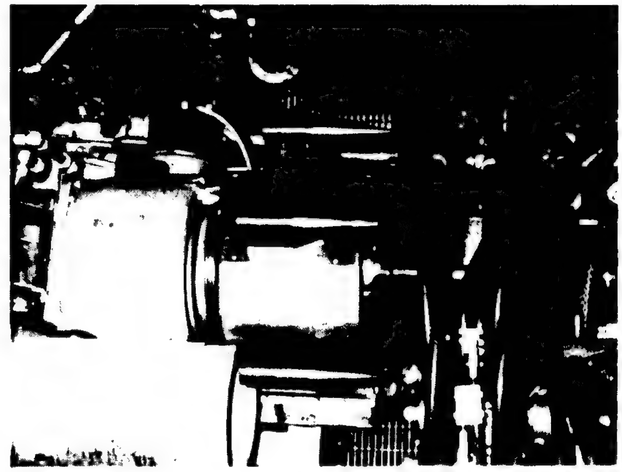
The Mach 6 facility is an intermittent blowdown, open jet wind tunnel, using pebble bed heater to raise the air temperature to required levels.



A technician checks the pressure transducer lines of the Mach 6 High Reynolds Number Facility.

The Mach 6 High Reynolds Number Facility can deliver air heated up to 1100 degrees R, and includes pitch sector and planform type support systems. In 1987 a connection from the exhaust to a vacuum sphere was added, increasing the Reynolds number range.

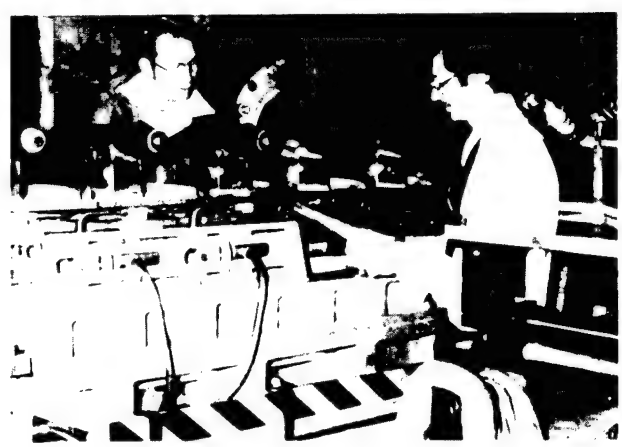
Heater section of the RENT with electrical cables and cooling lines.



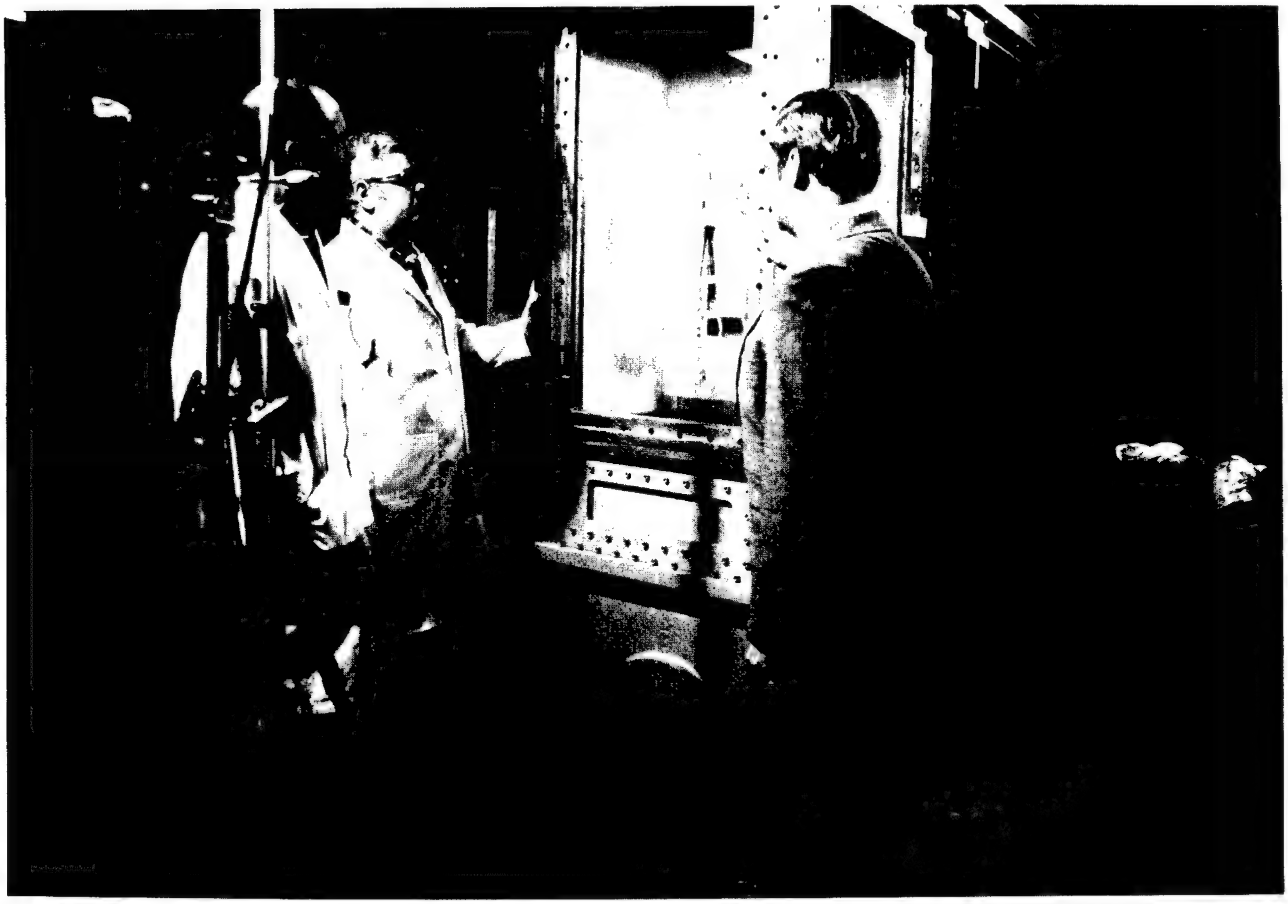
The Re-Entry Nose Tip (RENT) leg of the 50-megawatt facility used a rotary injector to hold test specimens.

The 20-Inch Hypersonic Wind Tunnel can generate Mach numbers up to 14 in an open jet test section; test models are mounted in a retractable pitch sector. This facility dates back to 1960 but has been considerably improved over the years. The Two-Foot Hydrodynamic Test Facility, first opened in 1986, uses inexpensive models and colored dyes to simulate a wide range of flight conditions, and provides data to supplement aircraft configuration design.

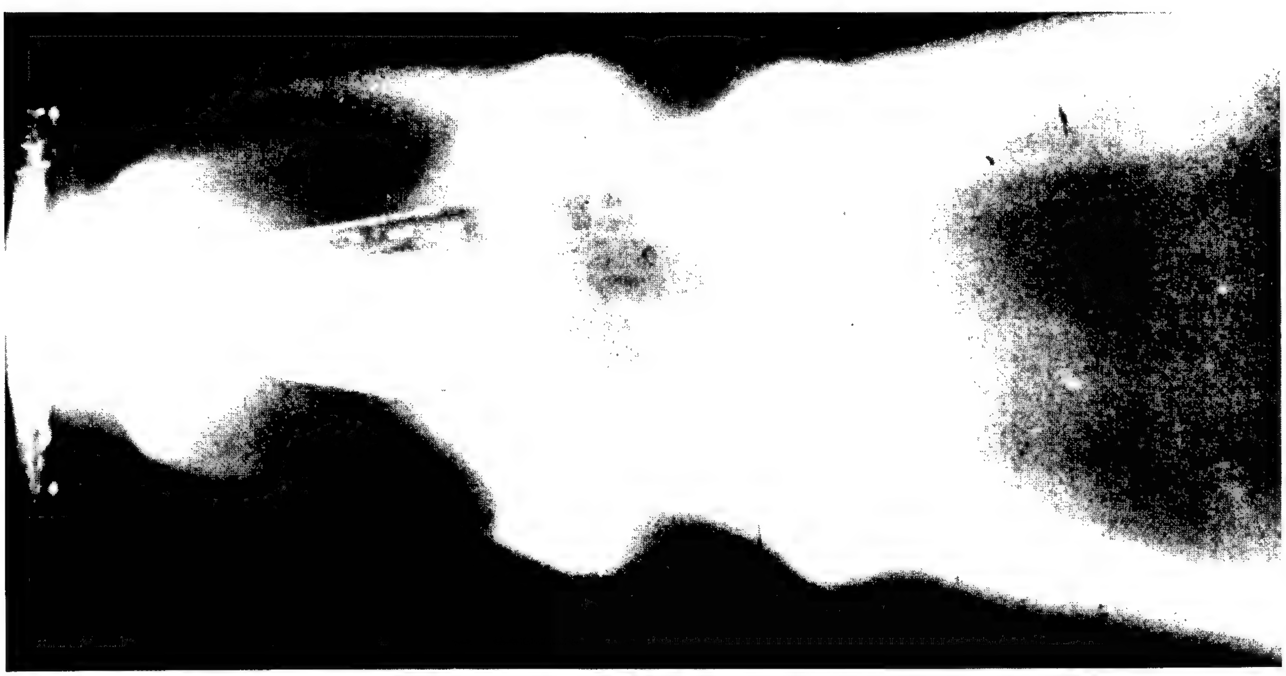
The Mobile Air Radiation Tunnel Facility, a Mach 2.5 blowdown tunnel large enough to accommodate models of up to 5.5 inches base



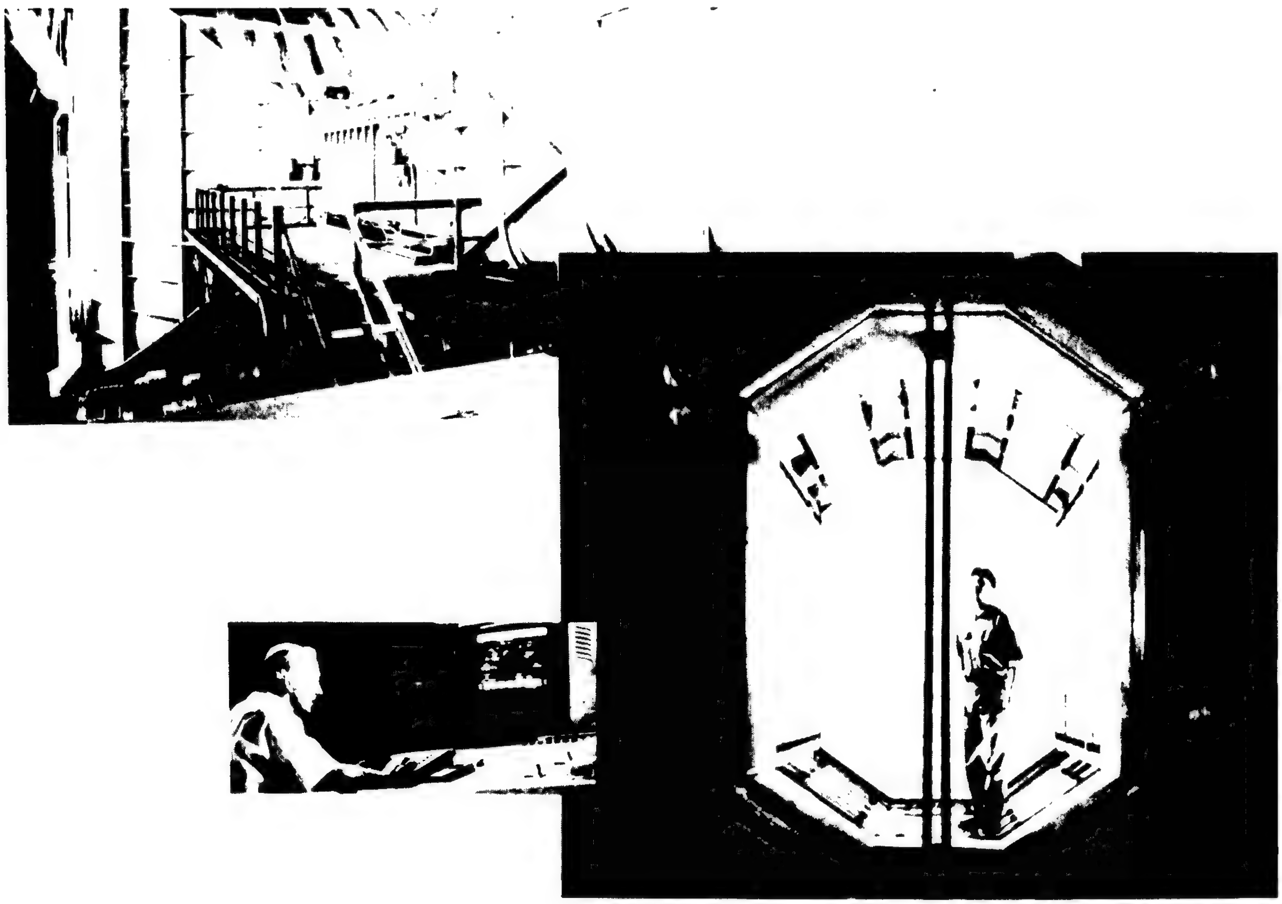
Engineers examine the rig to which nose cone ablation models are attached for testing in the RENT facility.



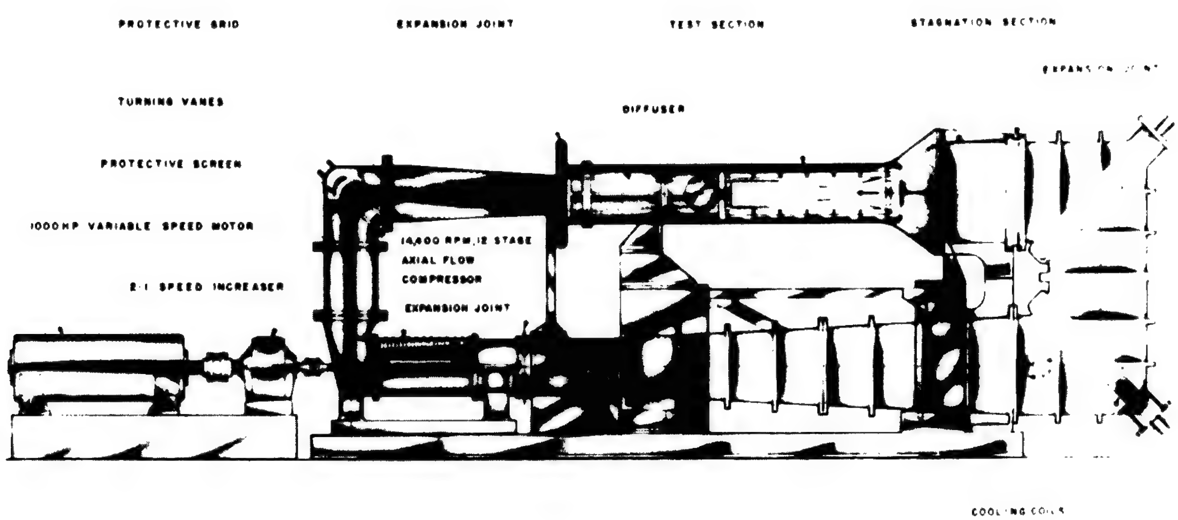
Large water tunnel, with a 2-foot test section. Used for vortex flow visualization with colored dyes.



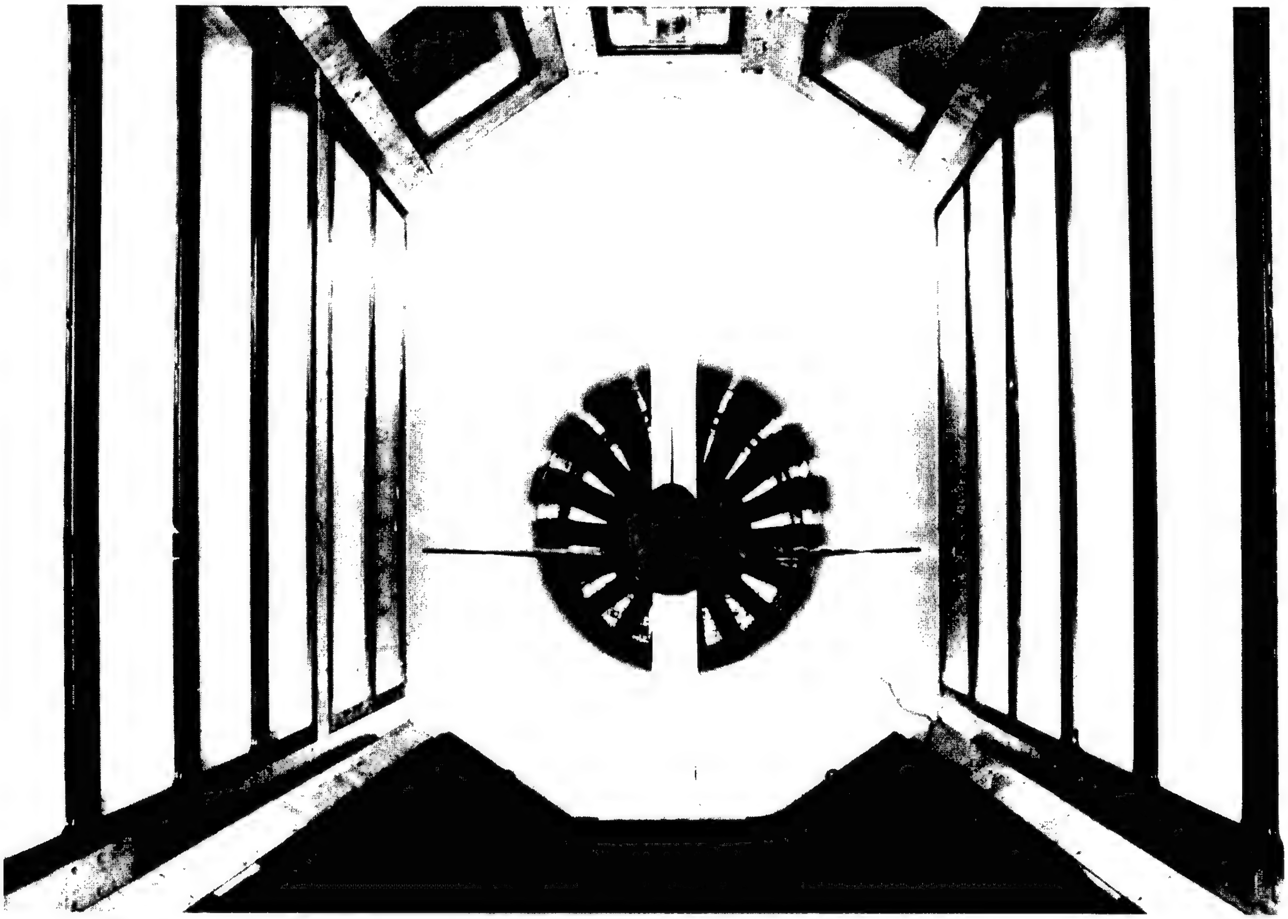
This nose cone is undergoing an ablation test in the RENT leg of the 50 MW wind tunnel.



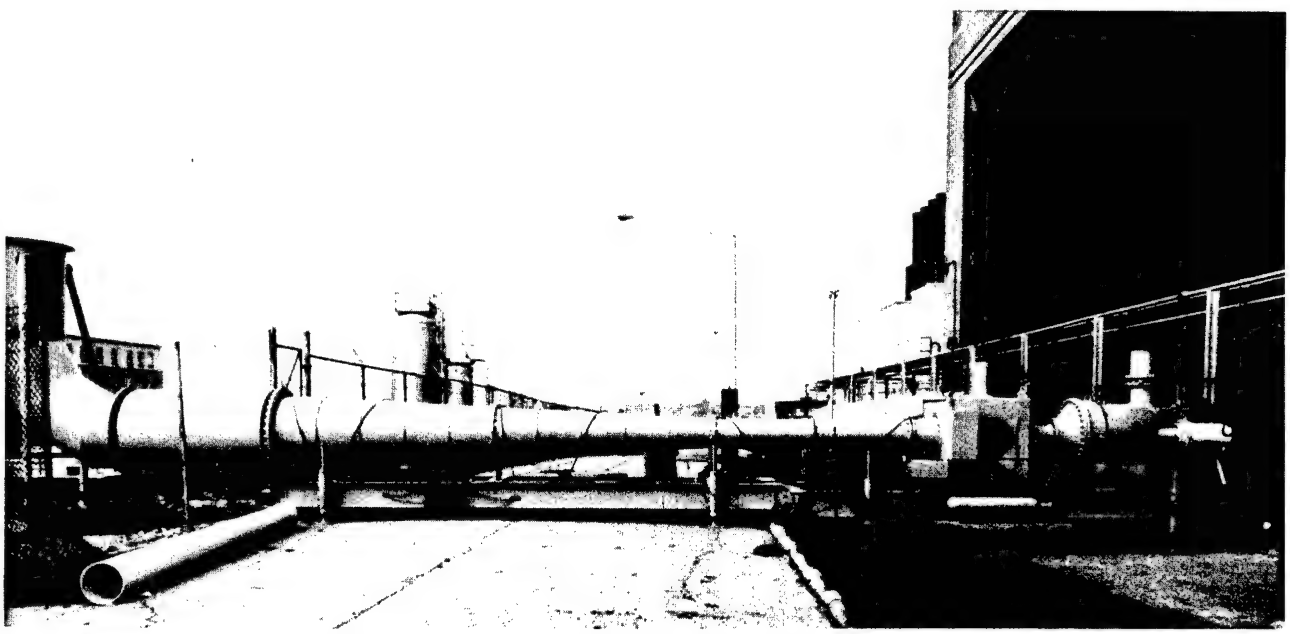
The test section of the SARL is 7x10 feet, surrounded by glass so that flow visualization work can be conducted. A platform allows easy access.



The WADC 6x6 foot supersonic wind tunnel was built in 1949 to test sealed configurations at Mach numbers between 1.5 and 2.5.



Model of a forward-swept wing in the SARL; fan blades in background.



This Mach 2.5 blowdown tunnel has been used in conjunction with the Materials Lab's 10KW flat top laser.

The large water tunnel was a cost-effective addition to the Lab's facilities, since it incorporated equipment already on hand.

diameter, is used to expand technologies such as laser hardening of radomes. It can be transported for testing with a variety of high energy lasers.

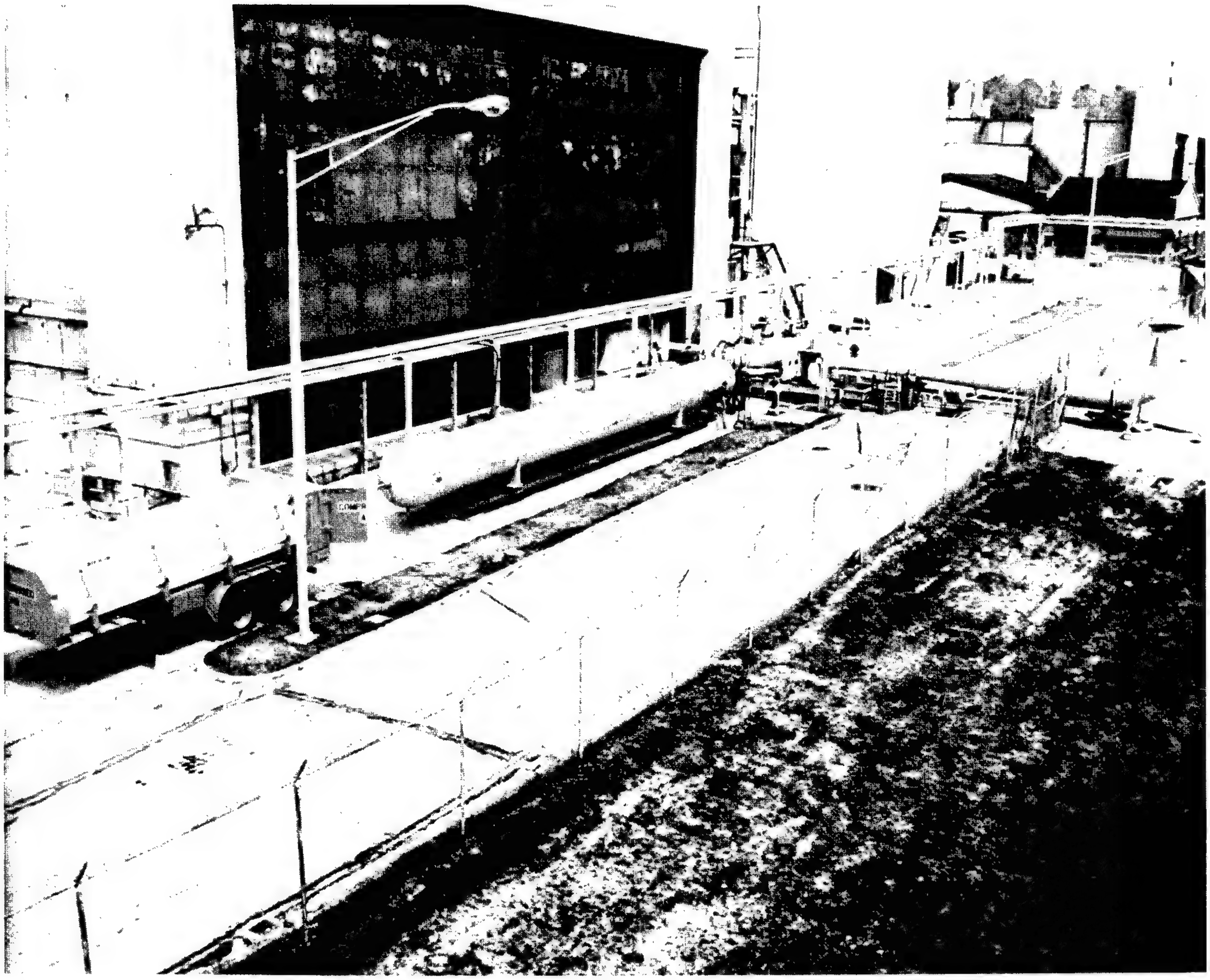
The Atmospheric Electricity Hazards Simulation Facility has recently conducted lightning qualification tests of the F-16. A Marx generator is used to discharge a capacitor bank, simulating actual lightning; symmetrically placed aluminum sheets serve as current return paths and simulate the electromagnetic field encountered in flight. An air-launched cruise missile was also successfully tested for lightning vulnerability.

The Rocket-Triggered Lightning Investigation has provided data for improving the protection of sensitive microelectronics in missiles and composite airframes. Tests were conducted atop Mount Baldy in New Mexico, using wire-and-rocket triggering units to attract lightning strikes to a cylindrical "Lightning Strike Object." Data on electromagnetic fields, lightning currents, and internal wire response were transmitted via fiber optics to an instrumentation van.

Planning for the Future

The Aeromechanics Division continues to lead the field in the development of advanced aerospace vehicle configurations. The renewal of interest in hypervelocity glide vehicles and the possibility of a National Aerospace Plane will profoundly affect the direction to be taken by this Division over the coming decade. Goals include the improvement of aerodynamic design methods, resulting in safer and more cost-effective development of weapon systems; ongoing research in computational fluid dynamics, particularly important to hypersonic development; and new aerodynamic heating and configuration cooling concepts. The Division expects to make major contributions to the integration of airframes and propulsion systems, which will improve the capabilities of all tactical and strategic aircraft as well as missiles. Aero configuration synthesis technology will improve wing design, weapon carriage, reduced observables, and vectoring thrust for the next generation of advanced fighters. Perhaps most important is the new work on hypervelocity vehicle technology, which will make possible hypersonic glide vehicles and the National Aerospace Plane, as well as supporting the efforts of the Ballistic Missile Organization (BMO). In addition, the Aeromechanics Division expects to improve its facilities and testing techniques.

Looking forward to the 1990s, the Aeromechanics Division expects to contribute to at least seven major ongoing efforts in other organizations. Aeroelastic tailoring technology, described in the next chapter, is concerned with multi-ply composites in aircraft structures. The orientation of the plies affects aerodynamics; by aeroelastically tailoring the composite wing, the designer can "instruct" the wing to curl forward as it bends up. Flutter problems and heavy structural reinforcements can be eliminated. The



Mobile Air Radiation Tunnel, used to test effects of a supersonic atmospheric laser encounter.

X-29 experimental vehicle has proved useful in the development of tailoring techniques.

Battle damage repair of composite structures (ABDR), a project of the Vehicle Subsystems Division, will also benefit from Aeromechanics research. Support will continue for adaptive flutter suppression in aircraft carrying external stores, permitting higher flight speeds and decreased exposure time to hostile environments. The Vibration Control of Space Structures (VCOSS) program and High Temperature Test Methods, projects based in the Structures Division, will be supported by Aeromechanics, as will structural improvement programs for operational aircraft and the aerodynamic aspects of frameless aircraft transparencies.

AEROMECHANICS CONTRIBUTIONS

DEVELOPED IN THE LATE 50s AND 60s	PAYOFF
• Tailormate inlet/airframe results	F-16 inlet
• Shock location uncertainties & shock freeze investigations	C-141, C-5A
• Integral-launch re-entry configuration analytical and experimental data base (ILRV)	Shuttle
• Wing-body blending	B-1, F-16
• Atmospheric research system to replace U-1 foil	RB-57F, WC-135
• Blunt body spike	Poseidon, Trident
• Variable geometry wings	ALCM/GLCM
• X-21	Hybrid laminar flow control ACFT

DEVELOPED IN 70's	PAYOFF POTENTIAL IN 80's
• Open bay carriage for weapon delivery	F-111 & other aircraft
• Supercritical wing (TACT program)	C-17 & modern transport ACFT, AV-8B
• Technology for powered high lift system & externally blown flaps	YC-15, C-17
• Flight demonstration of winglets	KC-135, Lear Jet, Westwind, Gulf Stream III, C-17
• Dynadec	F-16, F-18, ALCM, GLCM, B-1, F-15, ACM
• RV nose tips	Trident, Mark 4, Minuteman, Mark 12A

PURSUED IN 80's	USED IN 90's +
• Supercruise aeromechanics, inlets,nozzles and configurations	ATF
• Highly efficient survivable high speed configurations (aero & heating)	NASP, RVS
• Aero configured Missile	Adv. standoff air launched missiles
• PNS codes & advanced cooling	Maneuvering RVS
• High lift techniques & advanced nozzles with thrust vectoring & thrust reversing	
• Boost glide vehicle	Midgetman, HGV
• Reduced observables	Advanced missiles & aircraft
• Advanced testing & measurement capability	All future developments & systems improved confidence and reduced costs
• Expendable, partially reusable & reusable launch vehicle	Advanced launch system
• Variable camber wings	ATF
• High altitude aero & configurations	Long endurance flight vehicle

STRUCTURES DIVISION
FIB

STRUCTURES ADP BRANCH
(FIBA)

ADVANCED METALLIC STRUCTURES ADPO
ADVANCED COMPOSITES ADPO

STRUCTURES CONCEPTS BRANCH
(FIBC)

STRUCTURES SUPPORTABILITY/SURVIVABILITY
STRUCTURAL CONCEPTS EVALUATION DESIGN

STRUCTURES INTEGRITY BRANCH
(FIBE)

FATIGUE, FRACTURE AND RELIABILITY
LOADS AND CRITERIA

STRUCTURES DYNAMICS BRANCH
(FIBG)

DATA ANALYSIS
ACOUSTIC AND SONIC FATIGUE
INSTRUMENTATION AND ACQUISITION
VIBRATION

ANALYSIS AND OPTIMIZATION BRANCH
(FIBR)

DESIGN AND ANALYSIS METHODS
AEROELASTICS

STRUCTURES TEST BRANCH
(FIBT)

INSTRUMENTATION
PROJECT ENGINEERING
DATA ACQUISITION AND CONTROL
TEST PREPARATION

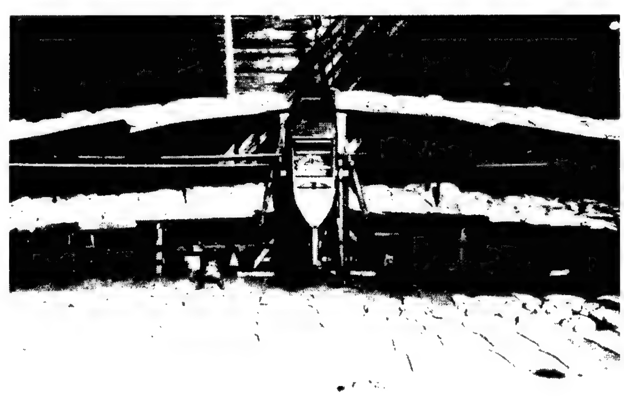
Structures and Dynamics

Structural development has always been a fundamental activity of the Flight Dynamics Lab and its predecessors. Though flight control, equipment and aerodynamics are essential for making an airplane fly, the plane itself could not be built without structures and dynamics technology. Static and dynamic loads and other stresses can be understood and predicted mathematically, but the Structures Division and its predecessors have played a central role in the entire process, from theory to actual design and construction of aircraft. The Division has developed test methods, validated criteria, and established specifications for many different types of aircraft. The process of developing a new structure begins with a study of the basic goals such as flight envelopes and weight limits. Next the preliminary size and shape of the airframe is laid out according to design criteria, and a formal stress analysis is performed to determine the adequacy of the structure. Full-scale structures tests follow, for fatigue life and flight loads. Much of this work is carried out by contractors, but the Flight Dynamics Lab provides the analytical and design tools, and double-checks every step of the process. When the actual airframe has been built, the Structures Division supervises final testing and integration with other aspects of the aircraft.

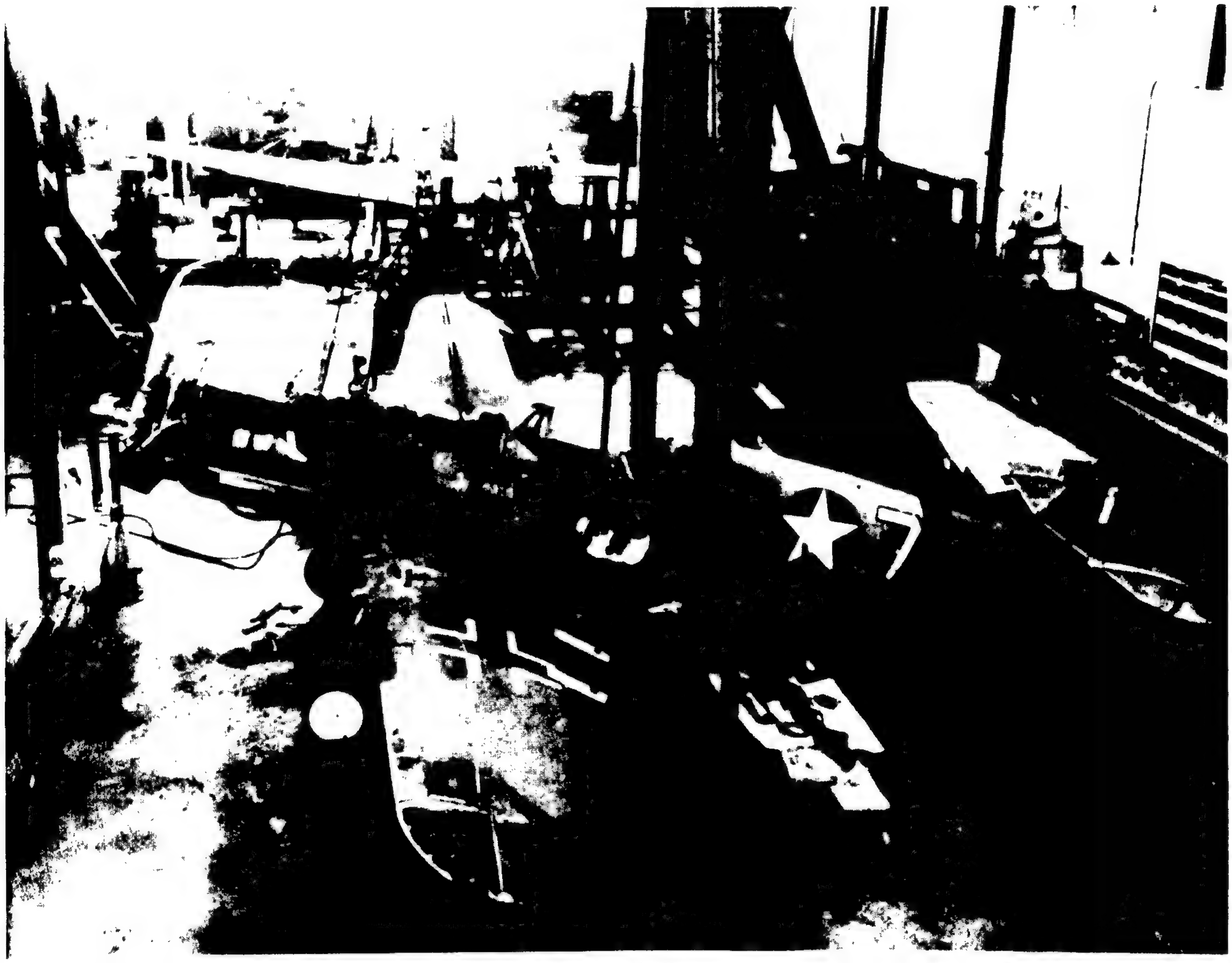
The Division works closely with the Materials Laboratory at Wright-Patterson, discovering applications for the advanced materials created by the latter. This partnership has led to applications for advanced materials such as graphite, boron and silicon carbide; and matrices such as epoxy, aluminum, titanium and aluminum-lithium. In the late 1980s metal-matrix materials and thermoplastic matrices are the most promising new materials.

History

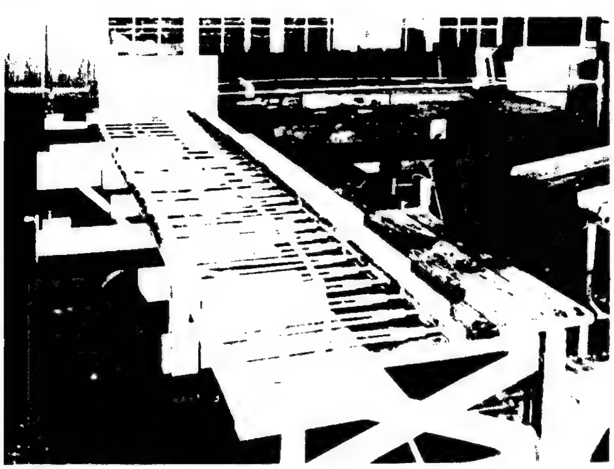
McCook Field had a static test facility as early as 1918, using shot bags,sandbags and log chains; a number of "firsts" came out of McCook during the years following the Great War. As time went on more sophisticated structural test methods were developed and made available to industry. Though McCook's methods seem primitive in comparison with what goes on today in Building 65, the Airplane Lab enjoyed a high rate of success: structural failures were quite rare in aircraft that had been tested there. Flight testing also dates back to the earliest days. "There are many who look askance upon airplane racing as a dangerous past time and a foolish waste of money and effort," an historian wrote in 1923. "Such people overlook the basic idea prompting these races: they are essentially tests; tests of design, endurance and performance for



DeHavilland DH-4 undergoing static testing at McCook Field in 1918. Note the sandbags on the wings.



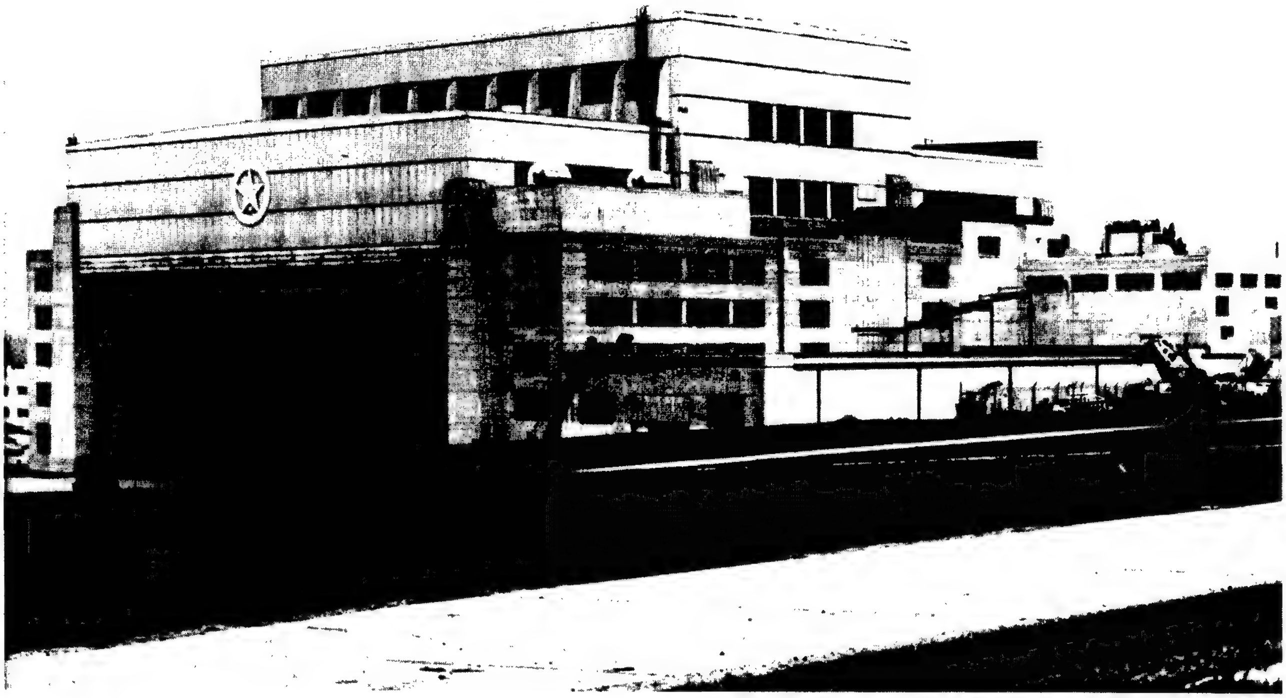
Static load tests were conducted on this captured Messerschmidt Me-109 at Wright Field during World War II.



Wooden wing under construction at McCook Field. Metal spars, stringers and skin have now replaced wood and fabric.

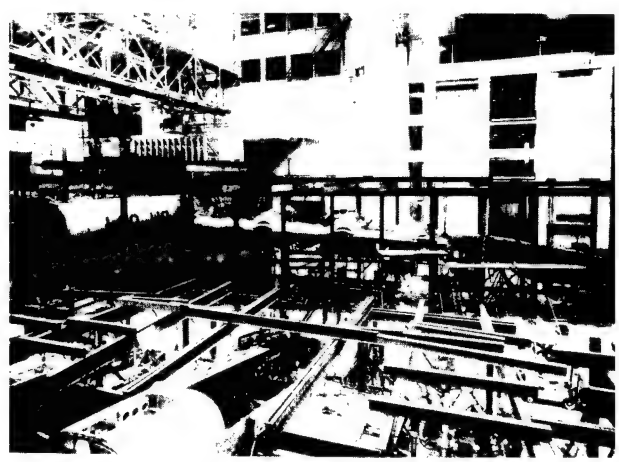
both airplanes and motors upon the results of which further advance in aeronautical achievement is predicated."

McCook engineers achieved world renown for their texts and handbooks prepared under the direction of Alfred Niles, chief of the structures lab, and Hugh Lippman. Slowly but surely the McCook engineers developed criteria for wing and fuselage loads, landing gear strength, and materials. Static testing at Wright Field was conducted in the Final Assembly Building (Bldg. 31) until the completion of Building 23, the Static Test Laboratory. With the military buildup before World War II this facility became inadequate and was replaced with the much larger Building 65 in November 1944.



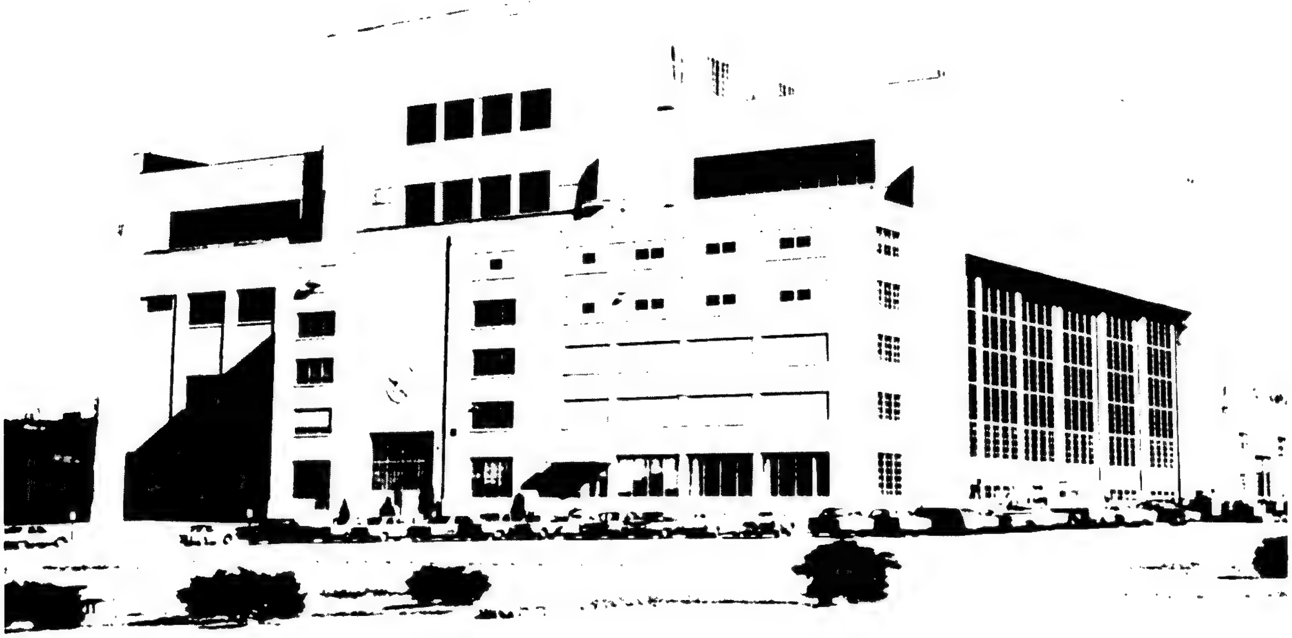
Since it was opened, the Structural Test Facility (Building 65) has tested over eighty different aircraft.

Shortly after the Lab moved to Wright Field, the Aeronautics Branch of the Department of Commerce established a board to review aircraft accidents, and a great amount of structural design data was compiled from this source. During the thirties structures research concentrated on increasing the payloads and improving all-weather capabilities of military aircraft. College professors from MIT and other institutions often worked at the Airplane Lab during the summers, contributing new ideas in structures technology; some of them used their experience to write textbooks.

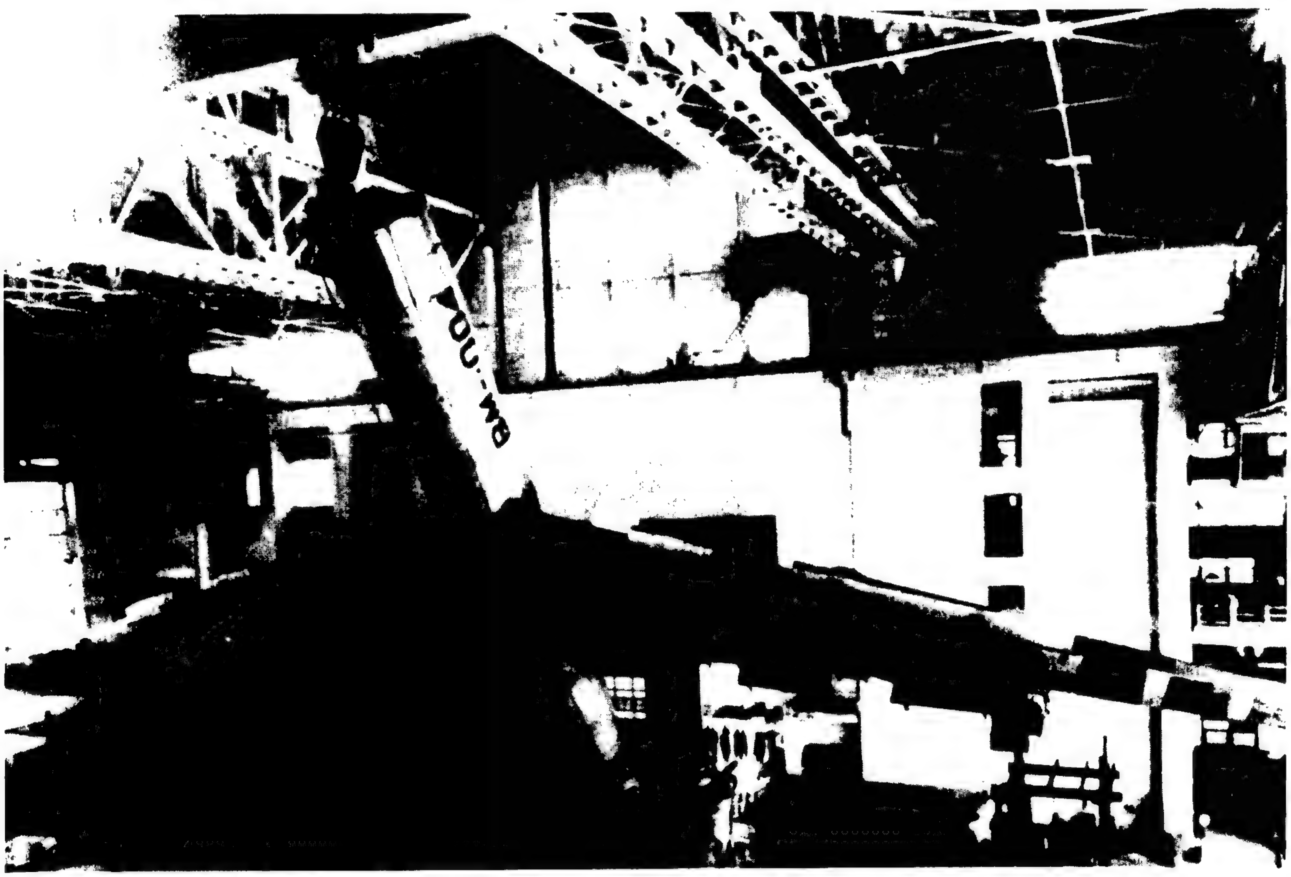


By World War II aircraft had become too large to test in Wright Field's old Building 23. The new Building 65 was constructed in response to this problem.

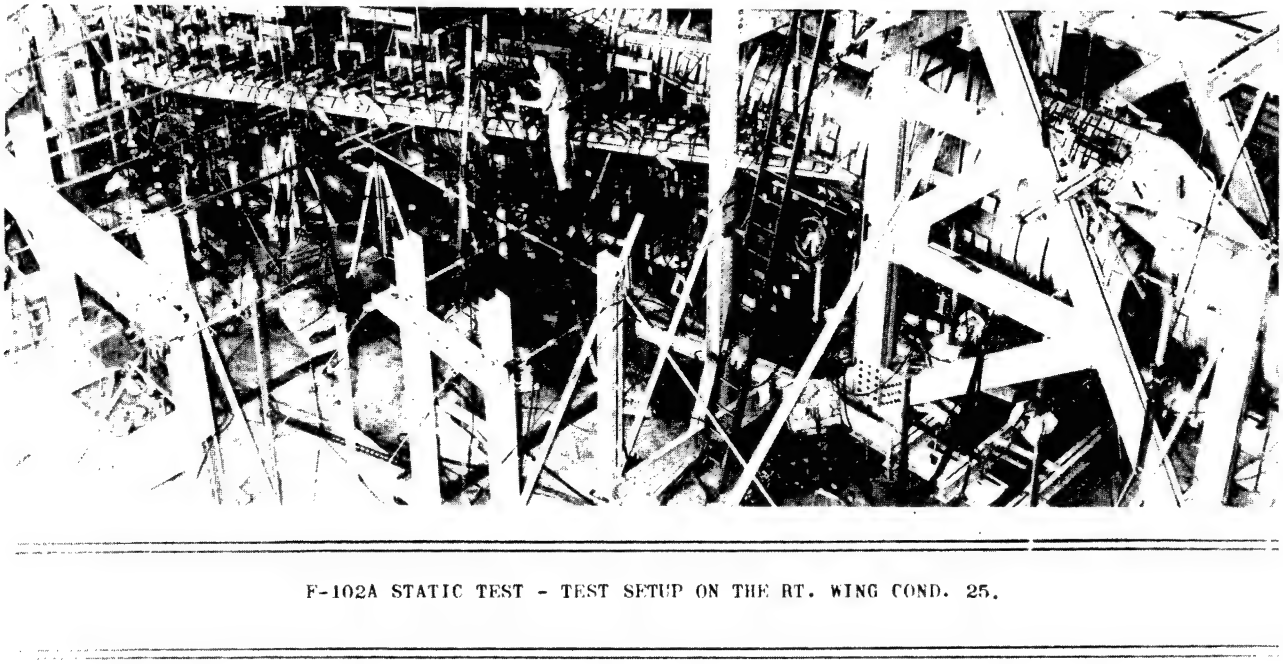
Before the Second World War almost all structures research was done in-house, but since that time the Lab has become partially dependent on contractors. At the end of the war, a new



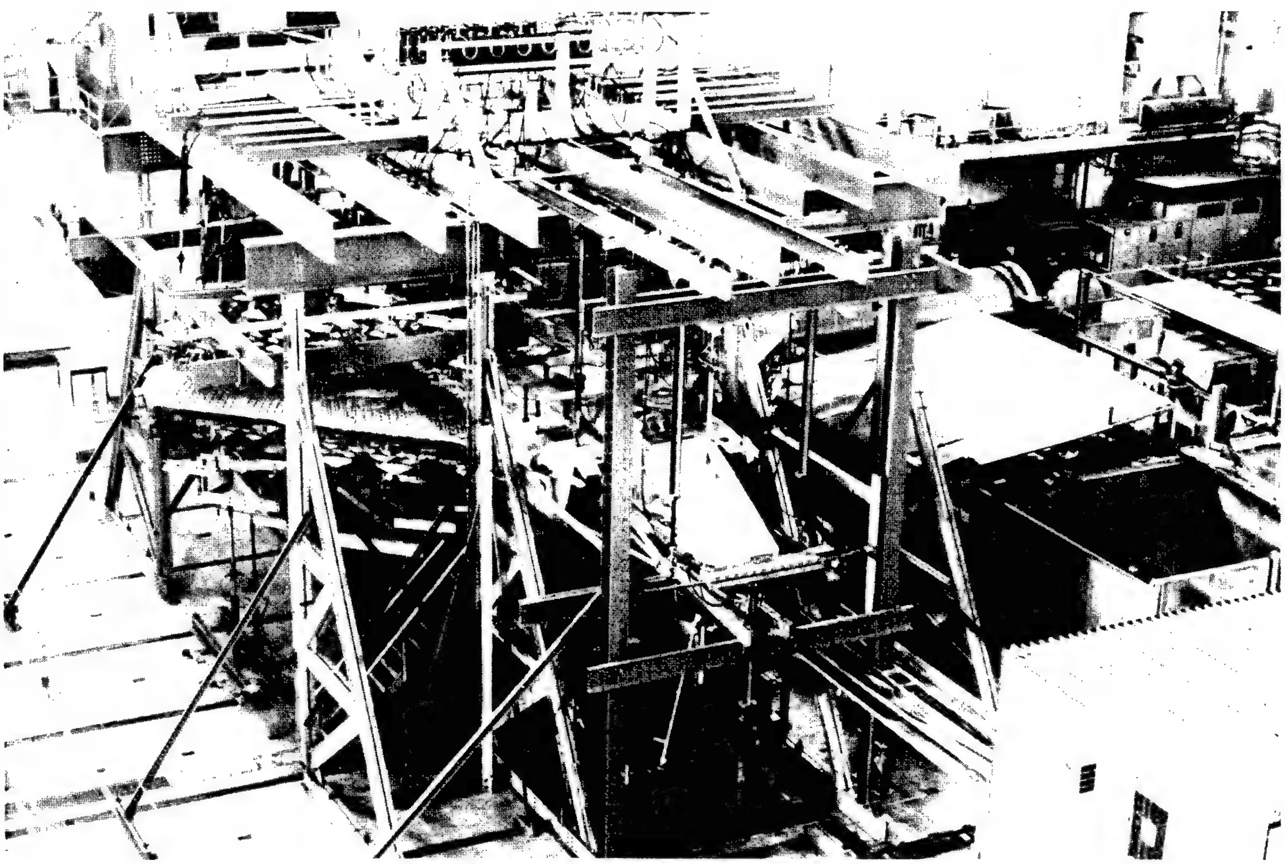
Building 65 had to be big enough to test a full-sized B-36 bomber, the largest plane of that time.



During the 1940s and 1950s, aircraft had to be turned upside down to get positive flight loads. In the case of the B-36, this was a monumental task.



Convair F-102A interceptor prepared for static testing of the right wing (1955).



F-15 undergoing dynamic load testing to determine its fatigue life expectancy and to test a fuel tank sealant.

emphasis was placed on improving stress analysis techniques; also, the Lab went back to static testing as a method of upgrading airframe structures. Using wartime data assembled by the Air Materiel Command, the Aircraft Lab demonstrated that better analytical methods for static testing were essential, and a variety of new tests were developed. The Aircraft Structural Integrity Program was conceived in the fifties. Among the unusual projects at the time was Project Redwing, which examined the effects of nuclear detonation on aircraft and missiles during bomb tests in the Pacific. This was one of the most active and productive periods for structural innovation -- things were moving fast, and many old-timers recall that informality was the order of the day, from lack of documentation to lack of neckties.

The Structures Branch operated Wright Field's structures testing facilities -- the world's most advanced -- after World War II, and a Structures Division was part of the Flight Dynamics Lab in the 1960s. Today the Structures Division (until recently the Structures and Dynamics Division) is responsible for structures research and development, and contributes to the updating of several military specifications.

Structures Analysis

Though the structures engineers of the Flight Dynamics Lab and its predecessors have always engaged in analysis of the airframes they help build, the development of digital computers in the 1950s permitted a quantum leap in the sophistication of analysis techniques. Since 1958 the Division has been using a computerized structural analysis program. Early finite element work and optimization development were among its pioneering efforts. With these advances, the analytical process has been both simplified and broadened to incorporate many diverse factors.

Structural weight reductions can improve the performance of advanced supersonic and hypersonic vehicles. Structures must be light and efficient without sacrificing integrity and safety. Mission profiles are analyzed to determine critical loading conditions, taking into account a wide spectrum of factors. Ultra-high loads and strain rates occurring in short time periods are complicated by stress-wave propagation in solids, blast effects, ablation, and thermomechanical loading of re-entry structures. More theoretical efforts, which will eventually benefit advanced vehicle design, include investigations of unified theories for thermal gradients and thermal stresses; advanced computer programs; behavior of elastic and viscoelastic materials; and hypervelocity impact. Since the early seventies the Analysis and Optimization Branch (under various names) has operated the Aerospace Structures Information and Analysis Center (ASIAC), a central agency for the collection, integration and dissemination of theoretical and applied structures data.

In 1978 the Analysis and Optimization Branch completed the technical work on a new computer-aided design program: STAGING (Structural Analysis through Generalized Interactive Graphics). The program, developed with the assistance of Battelle/Columbus, permits a design engineer to display the structural and material characteristics of a mathematical model on a graphics display computer terminal. This program was superseded by CADS (Computer Aided Design System) in the early eighties. The branch also developed FASTOP, a computer program to design aircraft lifting surfaces which automated first designing for strength, and then redesigning for flutter. A major success was Project ASTROS (Automated Structural Optimization System), a computer program that assists the integration of all the disciplines that impact the preliminary stage of aerospace structures design. ASTROS included analyses for loads, strength, vibrations, aeroelasticity and design-sensitivity as well as design-optimization. Programs and procedures for designing and analyzing bolted or bonded composite material joints were completed in the early eighties. At mid-decade Project SAMCJ (Strength Analysis of Multi-Fastener Composite

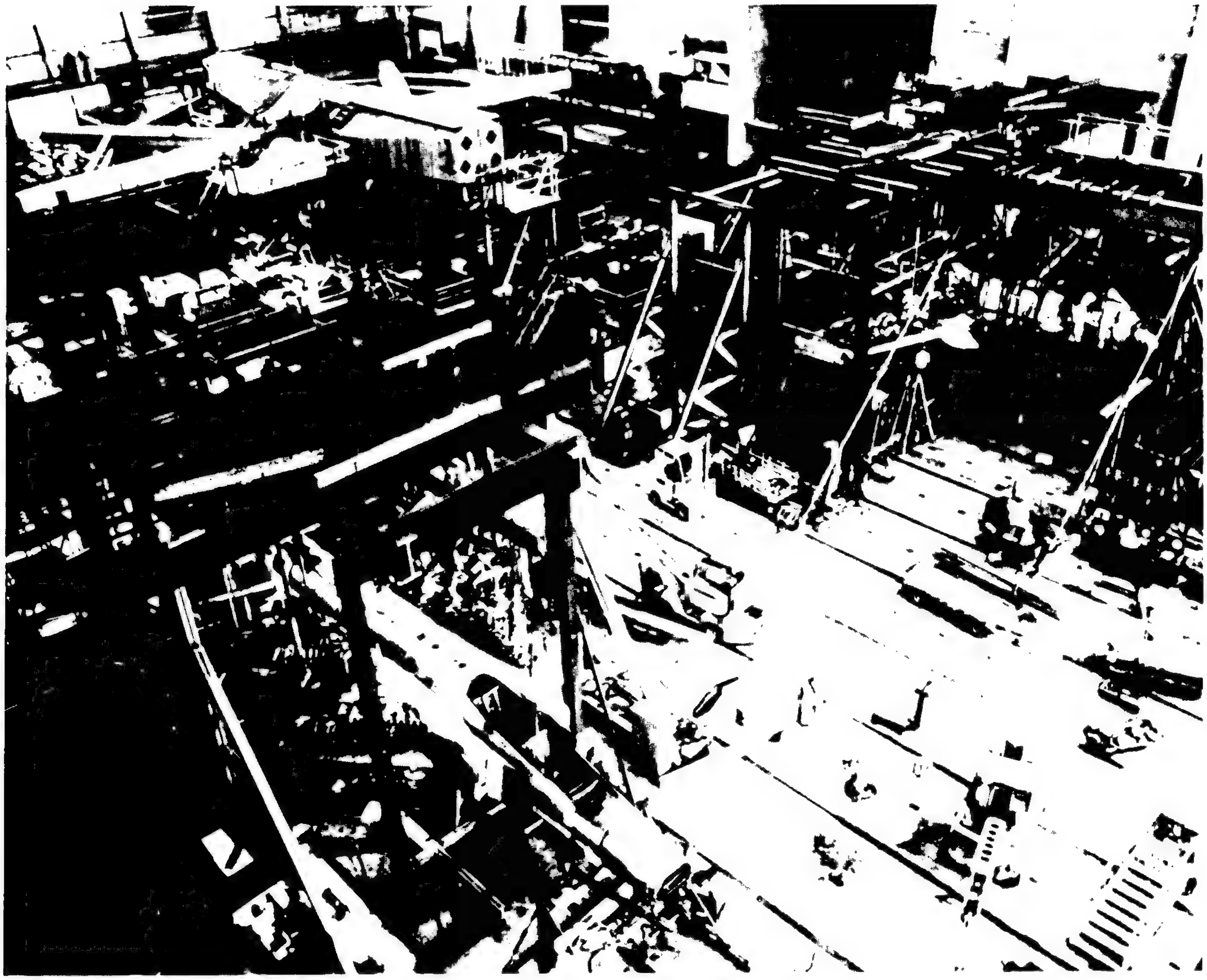
Joints) was a significant accomplishment of the branch, which also provided support for the ICAM (Integrated Computer Aided Manufacturing) program at the Air Force Materials Laboratory.

Every present and former Division employee interviewed for this book mentioned the computer as the single most important tool ever developed for structures design and testing. Not only do computers vastly expand the parameters of research, but they also have led to significant cost savings. At the same time, it should be remembered that there is no replacement for the intuition and common sense of an experienced engineer. The Structures Division is fortunate in having the best machines and the best people for the job.

Structural Loads

Since the early days of aircraft design, flight loads data have been recognized as a critical airframe factor, and the Airplane Lab was analyzing such information as early as 1931. Engineers at the Lab were among the first to recognize (in the words of William Lamar) that "the loads spectra to be used in the ground tests should be equivalent to the actual applied spectra in flight." Today this sounds like common sense; but without such an understanding, aircraft building would not have progressed much in the past half century. Velocity-load factor was the only readily available data before 1943, when better recording instruments permitted additional study of velocity-load factor as related to altitude. Data were collected from nearly every type of aircraft under every conceivable condition, including combat. Lab engineer Albert Epstein was responsible for the first structural specification X-1803, while his colleague Charlie Spere monitored the actual modification of aircraft in the shops. The analytical work conducted before and during World War II provided background and data for the handbook "Strength and Rigidity Specifications." After 1946 data gathered during the war were added, and a new series -- MIL-A-8860 -- was published. Most military and civil aircraft designed over the next decade used these specs. By now it was clear that structural criteria for jet aircraft were (as Holland Lowndes puts it) "unforgiving" -- the greater rigidity and higher performance of jets required very precise criteria. In layman's terms, high-performance jet aircraft fly higher, farther and longer than their predecessors, and so they wear out more quickly. During the late forties and early fifties stress and fatigue problems multiplied, and Structures engineers began searching for better design methods. In response to a series of B-47 structural failures, a complete overhaul of the specifications process was initiated in 1958. Robert Cavanagh, Bernard "Cliff" Boggs, Holland Lowndes, Fred Peck, Richard Hoener and others pioneered in the design of test methods during this period, and at present Sanford Lustig and his team work to keep the test methodology up to date. A large number of technical reports based on the new procedures have been issued by the Lab over the past three decades.

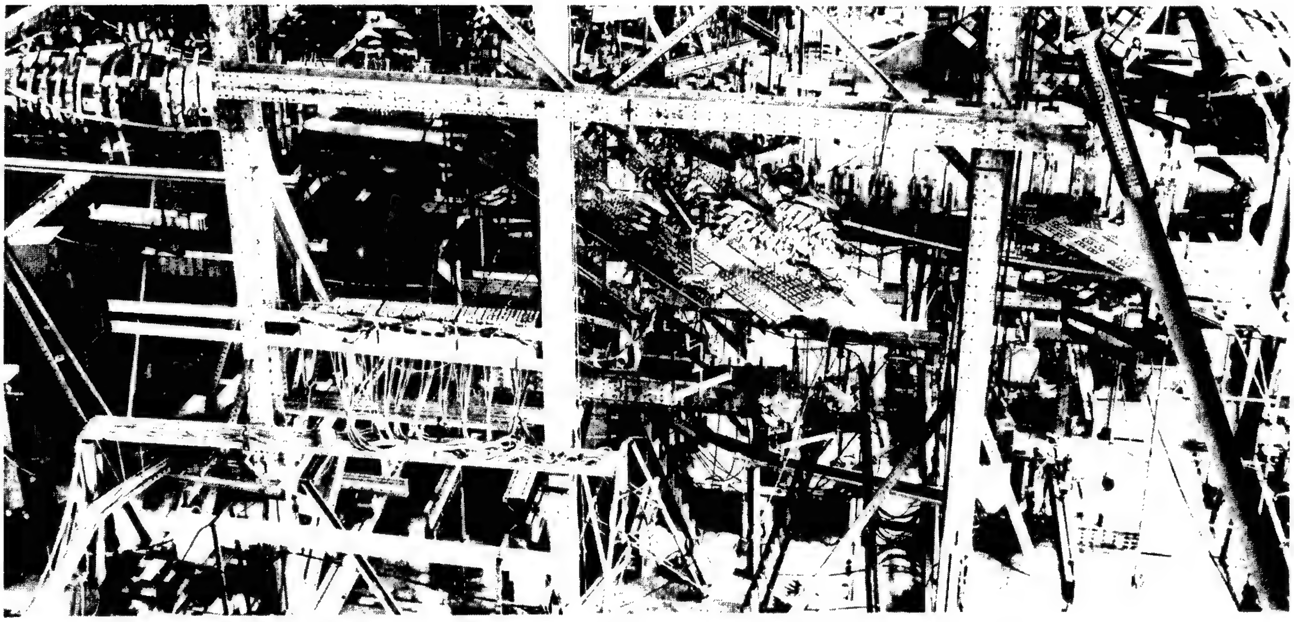
Structural fatigue is a field intimately related to flight loads. Any metal structure, if loads are applied with enough intensity and/or frequency, will eventually break. Fatigue failure was well known to nineteenth-century railroad engineers, who devised various methods of reducing metal stress in their rolling stock. The early Wright Flyers displayed similar failures, but consistent testing was not conducted until after World War II. During World War I a vast number of aircraft had to be built and put into service quickly, and not much consideration was given to lifespan. The second World War revealed that this area had been sadly neglected. Aircraft engineers were aware of the problem (then called crystallization) and its causes but there was no base point for the establishment of test criteria. Before the early 1940s the usual procedure was simply to replace the failed component. However, the enormous costs of World War II made American military planners painfully aware of the need for increasing the service life of aircraft and weapons systems. For the last four decades FDL has



The Structural Test Facility often has several tests going at once. Here engineers work on an A-10 static test, an F-4 C/D fatigue test and an Advanced Metallic Wing Carry-Through fatigue test.

worked more closely with the logistics community to increase the maintainability and lifespan of the technologies developed at the Lab.

During the war the Lab took its first small step in this direction, studying the fatigue failure of a B-24 nose gear, the Lab was able to duplicate the failure and find means of strengthening the gear. In 1945 an initial effort was made to duplicate fatigue failure in laboratory testing at Wright Field, using a North American AT-6 trainer. Criteria, although crude, had now been established, and considerable testing was undertaken in the late forties. Both military and commercial aircraft were now flying far more hours per year, and Structures engineers began to devote more of their time to the fatigue question. F-84 and F-86 wings from aircraft used in the Korean conflict were a useful source of data, and several crashes were investigated. F-84F wings were also taken from the production line and committed to fatigue testing as part of an article structural test program. This was a "first" for military aircraft and proved invaluable. Beginning with the Aircraft Structural Integrity Program (ASIP) the testing of "virgin" structures became a standard contract feature. New areas of concern, such as thermal and acoustic fatigue, were also discovered.



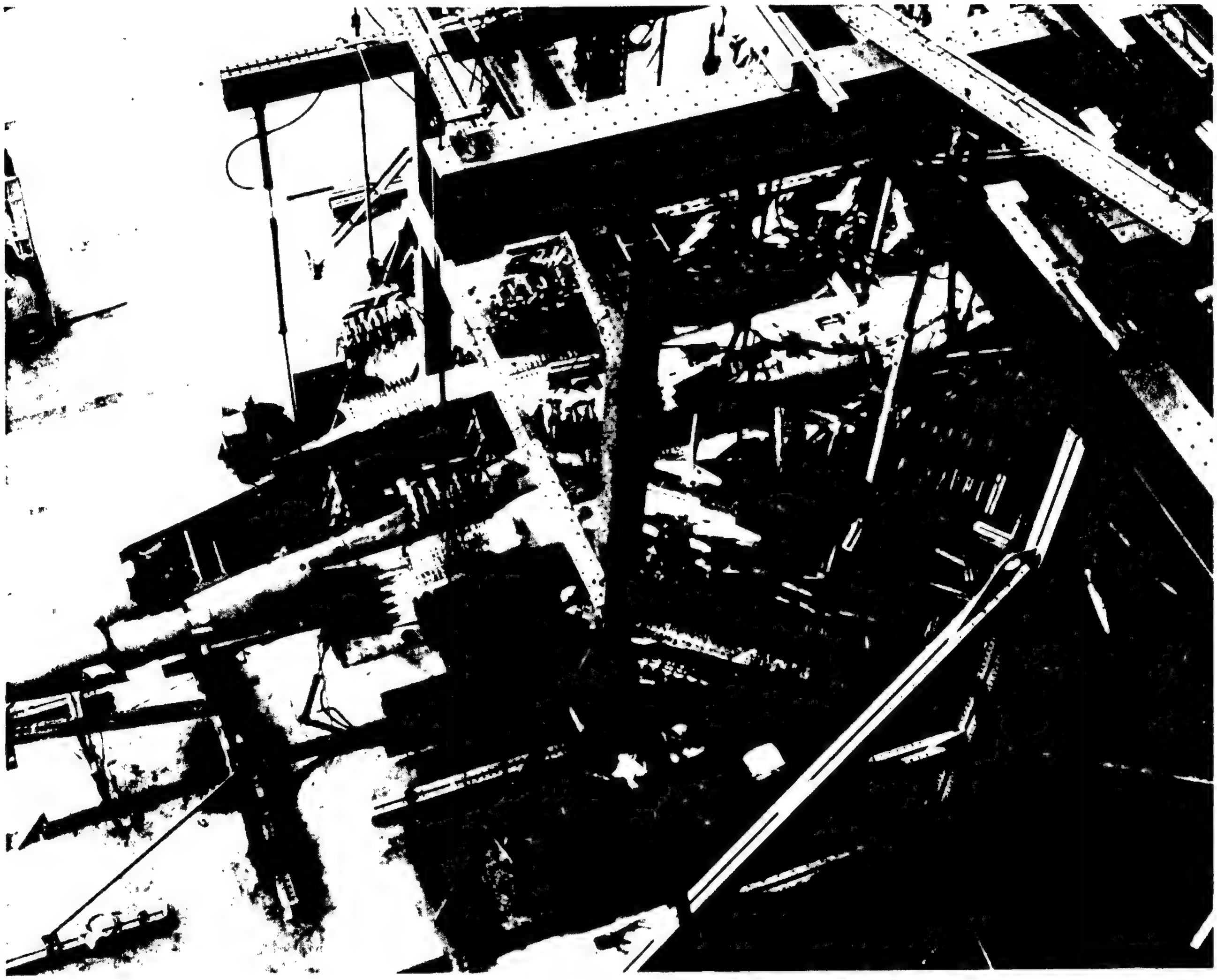
F-105D COND. PC-12-20-35-6 TEST SET UP

Flight loads are applied to this F-105D using hydraulic devices and pads cemented to the wings and body. Positive and negative loads can be applied by proper distribution of the pads.

The fatigue failure problem with the B-47 fleet in 1958 also pointed up the need for better facilities and techniques. Two of the three full-scale tests conducted after the fleet was grounded took place at contractors' plants; the Wright Field facilities were overloaded and could offer only technical assistance. It was becoming painfully clear that as the existing fleet aged, fatigue failures could not be predicted accurately, at least not with current facilities and methods. The Air Force ordered the Lab to develop reliable fatigue data both to protect the existing fleet and to aid in improving future designs.

The new criteria included requirements for service life, fatigue analysis and load spectrum, full scale tests, dynamic response flight tests, service load recording programs, and sonic fatigue. The Lab's criteria were first published in June 1958 and have been continually revised. An extensive structural integrity investigation was carried out and eventually covered most American military aircraft. By the end of the decade fatigue testing had been recognized as a major component of the structures engineering field, and had made considerable advances in all areas, including the unique requirements of the transonic and hypersonic regimes.

In the early seventies, requirements for damage tolerance (crack growth) were added to existing fatigue requirements . The Structures Division led the way in the development of fracture mechanics technology and analytical methodology to implement the new policy. Stricter attention to crack growth was expected to lead to greater survivability across a wide range of new and existing aircraft, but the results of this program went much further. Working with an F-111 fuselage, Division engineers developed criteria for durability and damage tolerance that literally revolutionized the structural design of aircraft. Few R&D programs have had such a far-reaching effect on the aircraft industry.

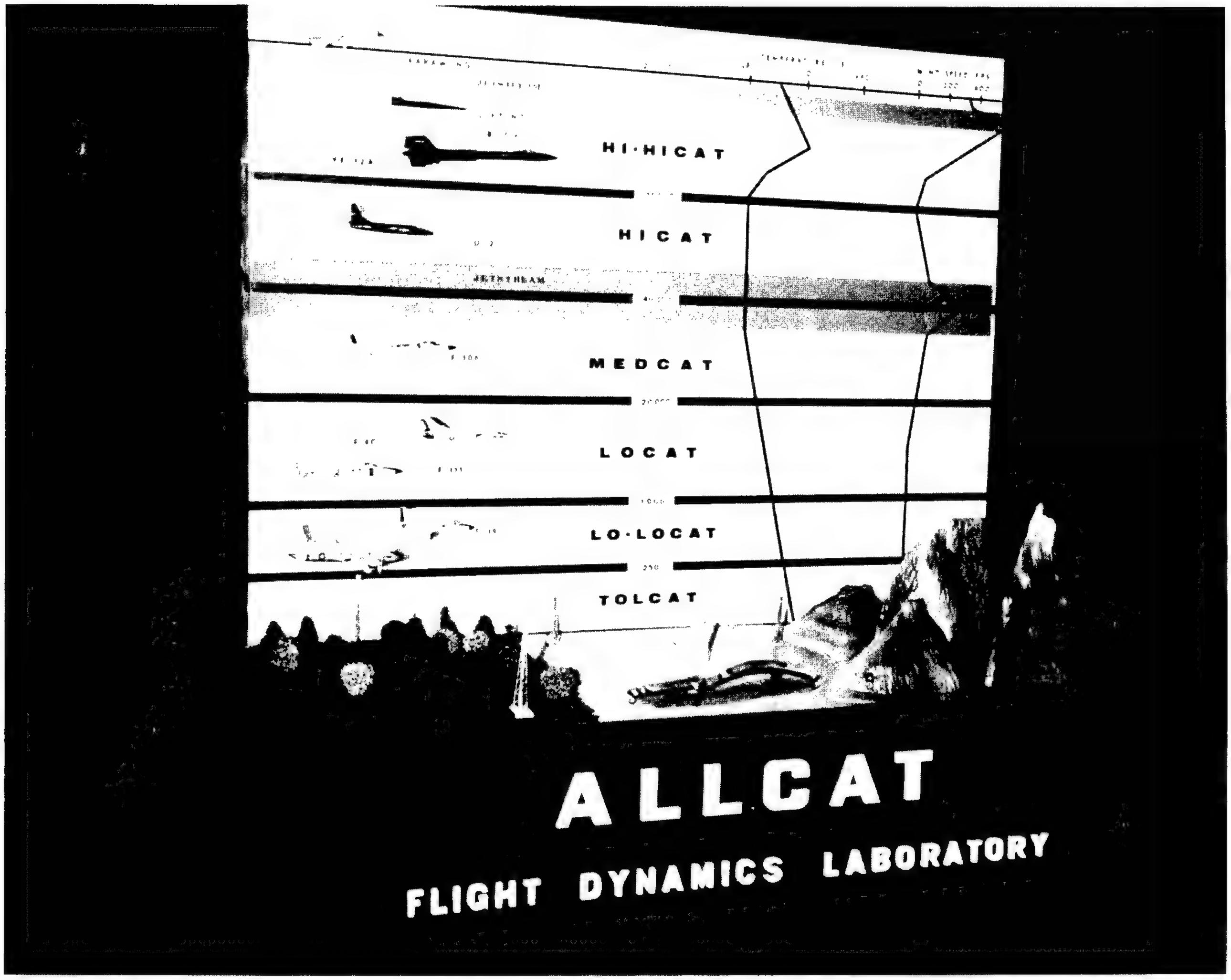


This life-extension fatigue test on an F-4 fighter greatly increased the lifespan of the Air Force's F-4 fleet.

F-4 flight testing a beryllium rudder under the guidance of the Technology Applications Branch. The rudder is 40% lighter than its aluminum counterpart, and passed all test with flying colors.

Other Advances in Structures Research

During the same period the Technology Applications Branch was working on a beryllium rudder and a Thermal Protection System for advanced high velocity vehicles. Development of survivability criteria and cryogenic technology continued. The Advanced Structures group had successfully tested a large hot (to 2100F) load carrying structure and a 6000 gallon liquid hydrogen tank capable of operation at temperatures between -427F and 1500F. Mathematical tools and models were designed for research in allied areas, such as the fatigue life of structures subjected to random loading.



The ALLCAT project set out to measure atmospheric turbulence levels at many different altitudes. AFFDL open house display, 1966.

The Experimental Mechanics Branch during the sixties was responsible for the Critical Atmospheric Turbulence (ALLCAT) project, an effort to provide turbulence data for all altitudes and seasons in heavily traveled geographic areas. Search missions were conducted at altitudes ranging from 250 to 70,000 feet over various regions; for example, ALLCAT data were collected by a U-2 aircraft over Puerto Rico and the continental United States.

Advanced Structures and Materials

Choice of materials was one of the first real airplane design problems. The Wright brothers, Langley and others experimented with a variety of airframe materials, and of course all early aircraft were constructed of lightweight woods. Before World War I the Europeans experimented with metal aircraft, and had some limited success during the war. But American researchers believed for a decade afterward that metal planes would never be practical. In the late twenties private industry was beginning to have some success with aluminum airframes, but the Materiel Division at McCook Field lagged far behind in applying this concept. In 1931 and 1932, however, the Airplane Lab evaluated two twin-engine, cantilever wing, all-metal monoplane bombers. The Martin XB-907A was accepted and developed into the B-10. The

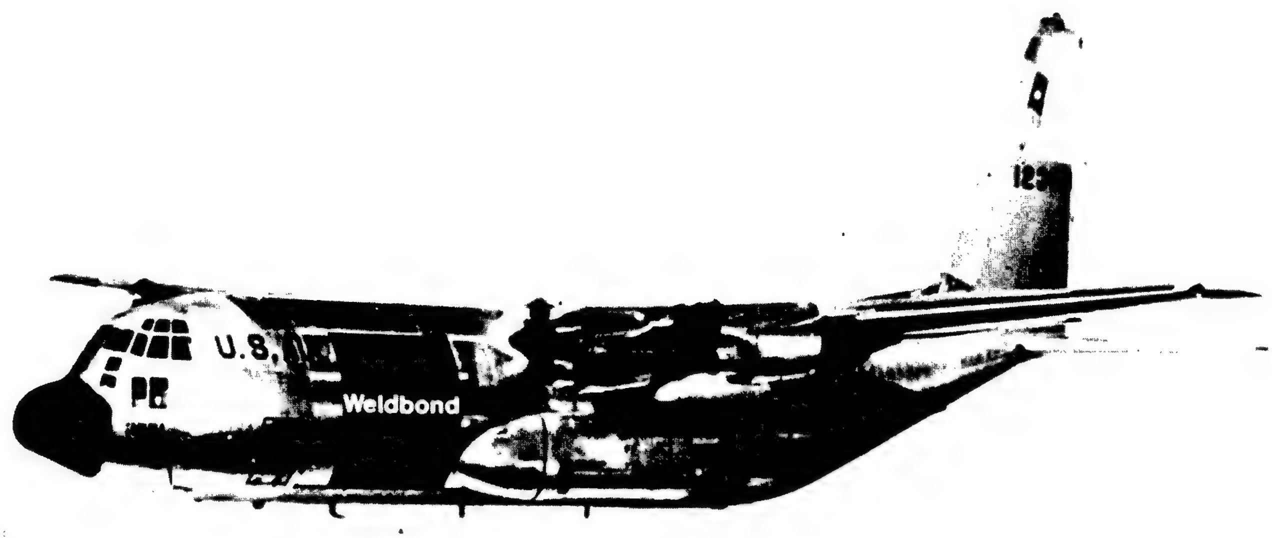
Boeing XB-901 was rejected, but soon became the basis of the company's 247, an early metal commercial airliner. By the early thirties the DC-1, DC-2 and B-9 were in the air; soon afterward methods were developed for fabricating stainless steel and magnesium airframes. It was discovered that all-metal monocoque airframes could be far more efficient than wood, because the skin becomes a load-bearing structure. Aluminum came to be the most commonly used material, and still is, though as Holland Lowndes points out, "There's so much difference between the first aluminum and today's aluminum, that you can't just say 'aluminum.'" Titanium, magnesium, steel alloys, and composites have also become essential. World War II brought a revolution in materials research: for example, in 1944 the Airplane Lab built and flew an experimental AT-6 with fiberglass, balsa-core wings in 1944. By the time the Air Force became an independent military service, Wright Field was again the leader in the identification and testing of new materials.

The new generation of supersonic jet aircraft which emerged in the 1950s required entirely new types of lightweight structural materials. While they are often stronger and more durable, these materials are expensive, and the cost factor has often led to a search for simpler and more

In the early 1930s the Airplane Lab evaluated this B-10 bomber before choosing it for production.

maintainable systems. The Lab pioneered in the application of advanced steels and titanium for airframe construction, as well as a variety of nonmetallic materials. The lab built and successfully static tested a magnesium wing for the F-80, and later a completely magnesium F-80 (except for the landing gear) was constructed. In addition, the leading and trailing edge structures of the B-36 wings were magnesium. Bonding techniques originated at the Lab in the late forties, beginning with a process called "cycle bonding." The adhesively bonded metal sandwich technology developed by industry under the guidance of the Structures Division is used in virtually every aircraft manufactured today. Welded structure technology was improved for the X-15 and B-70 and for such high-temperature applications as the X-20 Dyna-Soar experimental plane. Efforts to reduce airframe weight resulted in the brazed sandwich concept, and new types of mechanical fasteners were developed for supersonic and hypersonic aircraft. High-temperature re-radiation needs for reducing structural weights spurred research into such refractory metals as molybdenum and columbium for the ASSET and X-20 programs, both of which produced data that are now being used in hypersonic research. A ceramic filled open-face honeycomb structure was designed and first used in the firewall of the Saturn booster rocket.

The Applied Mechanics Branch was responsible during the sixties for exploring a variety of new structural approaches. The effective combination of metallic and nonmetallic materials, thermally-protected and heat-resistant concepts, the collection and publication of technical data, and the development of flight data recording were among its tasks. Studies were conducted on beryllium, new materials for fastening and joining, deployable lifting surfaces, and meteoroid and radiation protection. The Branch developed new design concepts combining sandwich, monocoque and shell structures with ablation and active and transpiration cooling techniques. In



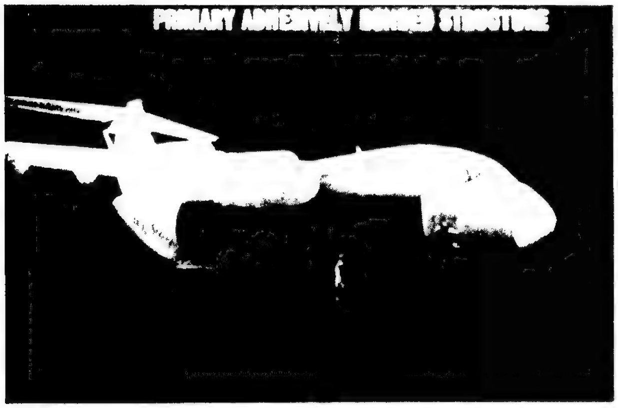
Weldbond forward fuselage side panel on a C-130H aircraft, installed for extended in-service evaluation.

the mid-sixties the first studies began on cryogenic fuel tanks; this was to become a major effort in later years. Other projects included structural use of dispersion strengthened metals, superalloys, and refractory metals in medium and high L/D systems; impact response of transparencies; survivability to gunfire; and development of an installation guide for airframe manufacturers of parasitic armor.

After the reorganization which created the Structural Mechanics Division, materials application research was carried on by the Structural Concepts Branch. New efforts in the early seventies included the evaluation of the Weldbond concept, which was flight tested on a C-130H aircraft. Weldbond, curiously enough, was first "discovered" in Vietnam, when a downed Soviet-built aircraft was examined. American engineers worked for years to duplicate the Soviet process, eventually dubbed "Weldbond."

Various other bonding techniques, important because they eliminate structural fasteners, have been a major effort in materials research during the last several decades. In 1967 the Lab contributed to the development of all-titanium airframes, a concept applied most successfully to the then top-secret SR-71.

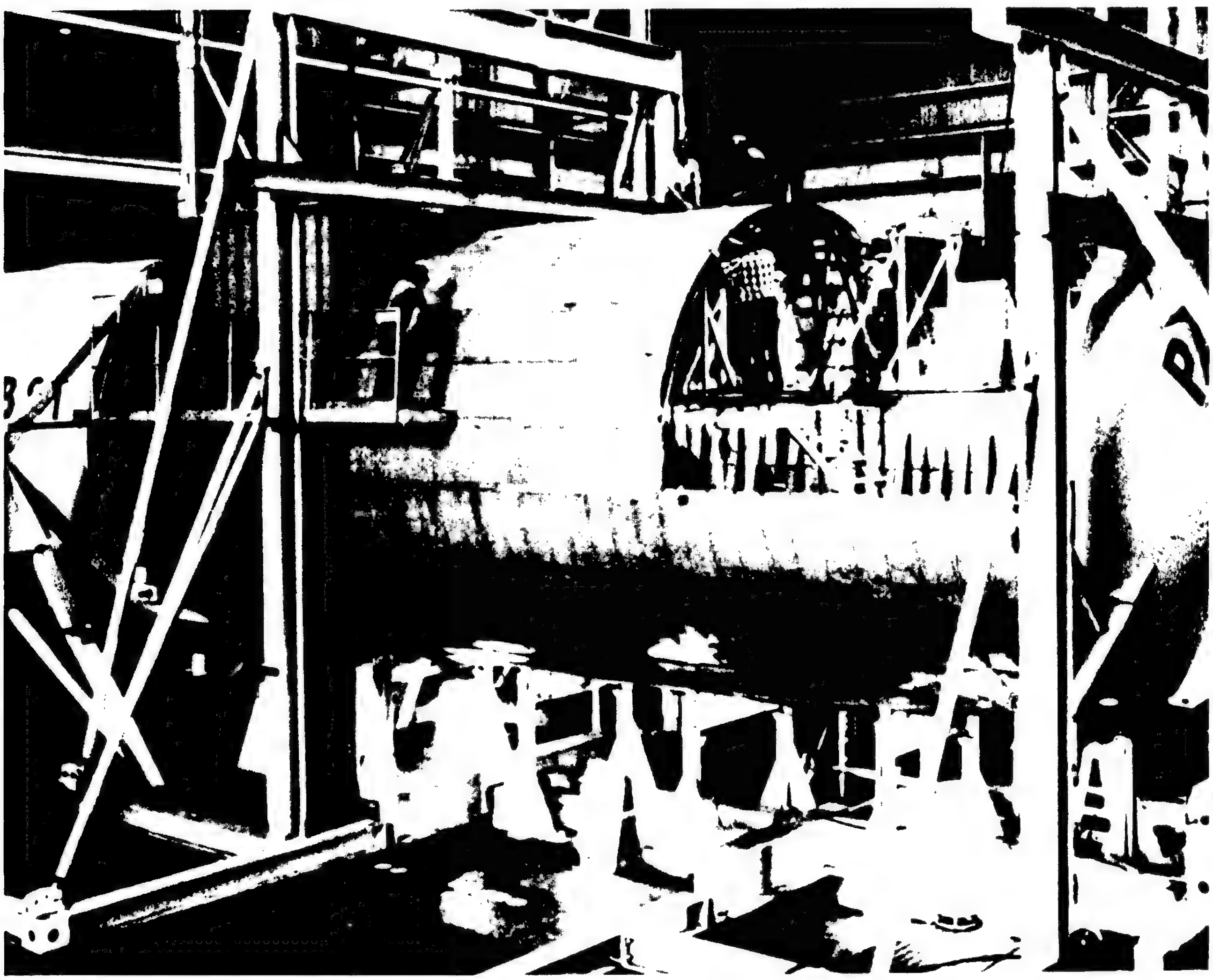
As the seventies ended several other advanced development programs also met with success. The Primary Adhesively Bonded Structures Technology (PABST) program fabricated a full-scale YC-15 adhesively bonded fuselage and tested it for fatigue and damage tolerance. Flaws



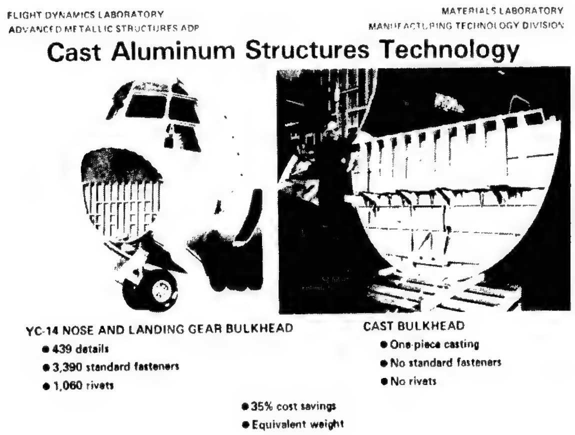
YC-15 prototype incorporating a PABST body section for fatigue and damage tolerance testing.

were deliberately introduced to reveal any bonding weaknesses, and results exceeded expectations when the program was completed in 1980. A four-by-six foot fuselage panel was tested further for a variety of environmental stresses. AFWAL TR 80-3112, "Primary Adhesive Bonded Structure Technology Full Scale Test Report," was published, and a technical paper was delivered by William Shelton at an American Society for Testing and Materials symposium.

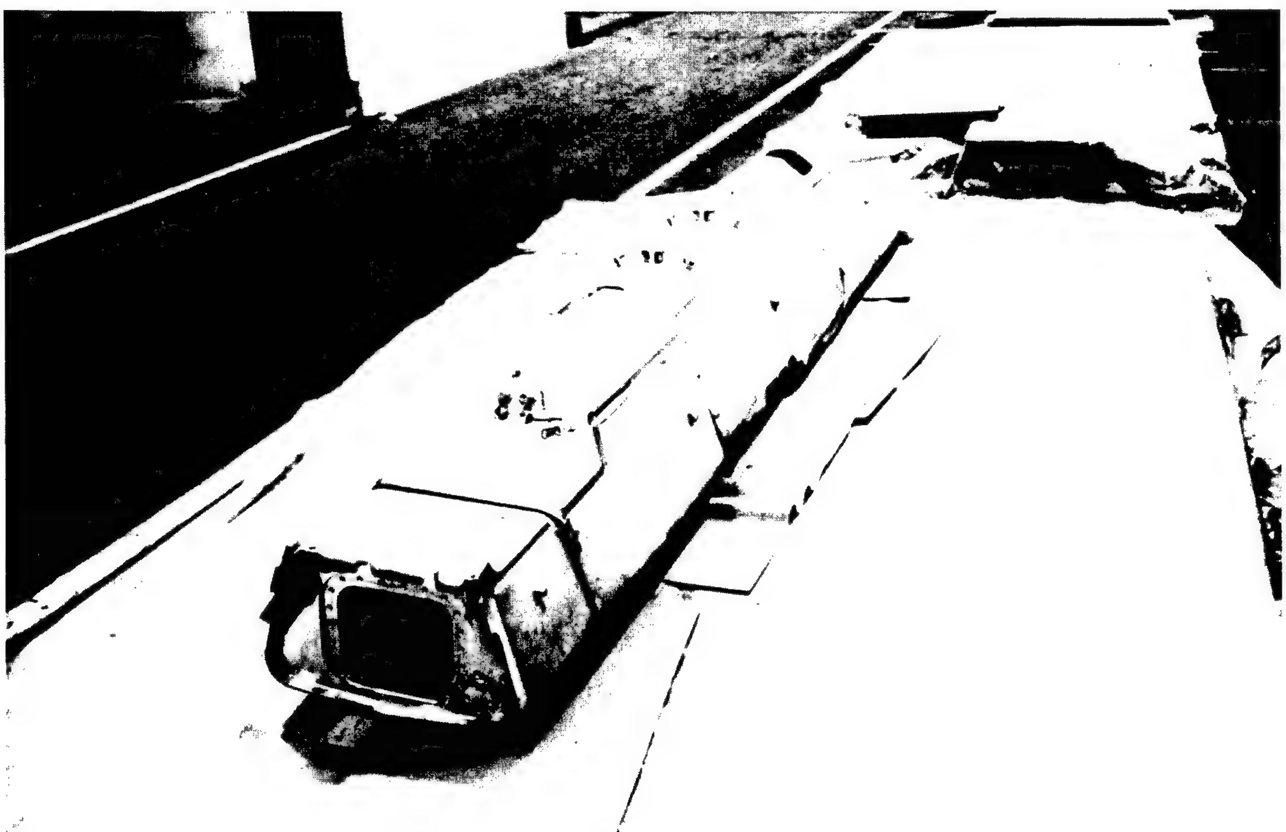
The Branch next initiated the Cast Aluminum Structures Technology (CAST) project, which resulted in significant improvement in the fatigue



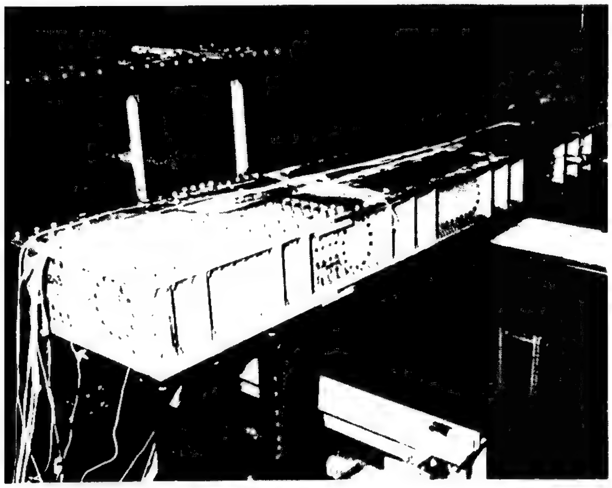
PABST wide-bodied cargo aircraft structure.

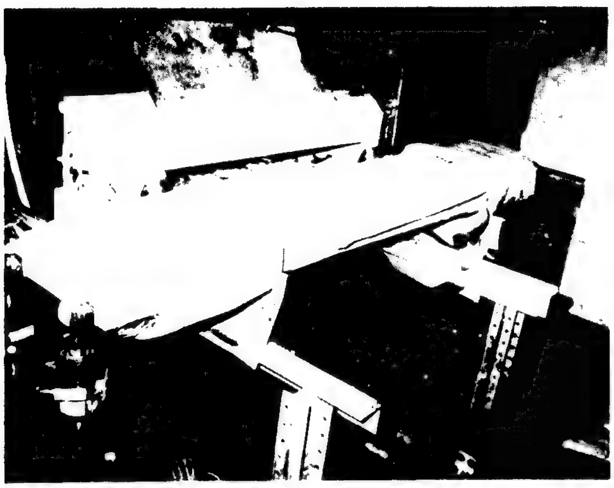


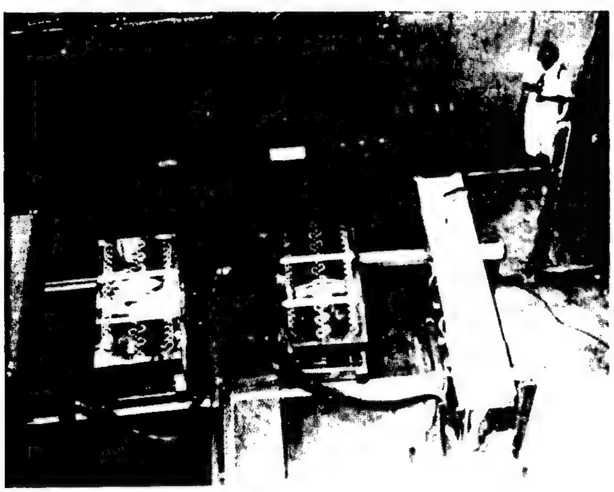
This Cast Aluminum Structures Technology project developed a one-piece YC-14 bulkhead at a cost savings of 35% below conventional manufacturing processes.



The first application of CAST technology was this ACLM body.







Some of the aircraft fuel tanks tested by the Structures Division. Test facilities can vary the environment of the tanks and can run JP-4 jet fuel through their systems.

life of castings. The first application of this technology was in an air-launched cruise missile.

The Branch also contributed to the Integral Fuel Tank Design Handbook, an AFWAL project initiated to correct aircraft design errors that had resulted in fuel tank leaks over the years. Lab employees recall starting from scratch on this project: no one had ever really thought about comprehensive testing for fuel tank leaks. The first edition was published in 1979, and a fuel tank test facility was constructed in 1981. A 37-month program was completed in 1982, accumulating a large data base and resulting in an advanced analytical method for predicting fatigue of aircraft fuel tank skins precipitated by fluid/structure interaction. Once again the Flight Dynamics Lab had created new test methods and attracted much attention from both industry and the military. Based on this research, several contractors are now exploring new concepts in fuel tanks.

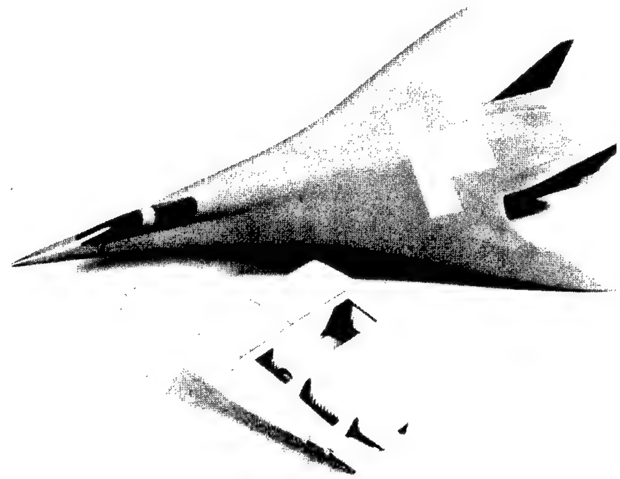
During the same period the Division conducted the AMAVS (Advanced Metallic Air Vehicle Structure) program. Structures engineers tested a full-scale, advanced wing carry-through structure for the B-1A. The structure made extensive use of high-strength steel and advanced titanium alloys, and resulted in an 80% cost and 50% weight reduction compared to the production design.

Perhaps one of the most significant contributions of the Aircraft and Flight Dynamics Labs to aircraft structure has been the successful application of metallic and non-metallic composites. Almost no aircraft flying today would be possible without these advanced materials, and the Structures Division has always been at the forefront in applying composites. In the early 1940s the Air Corps initiated research on glass fabric polyester composites for airframe components. These laminates had been successfully used in radomes, and engineers now designed a monocoque aft fuselage section for a BT-13, and a fiberglass outer wing panel (built in-house) which was flight-tested in two AT-6 trainer aircraft. Although other projects took

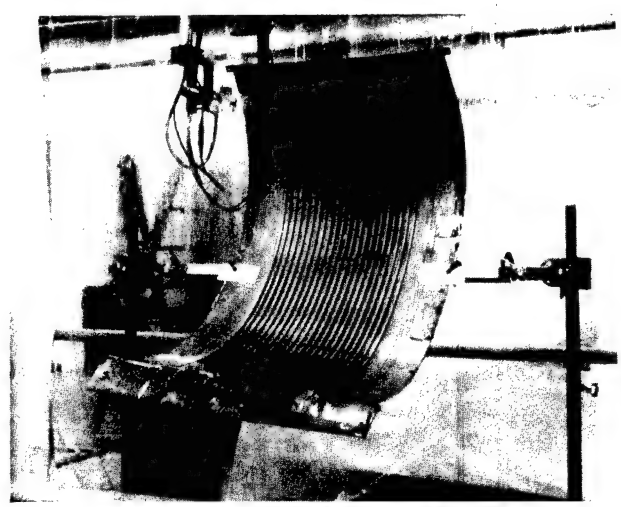
priority after World War II, the feasibility of such composites had been demonstrated. The new generation of high-performance aircraft developed in the fifties could not use composites in most applications. But rapid advances in materials technology, the special needs of aerospace vehicles, and the findings of Project Forecast (1963) led to a renewed interest in composites. The Structures Division was in the forefront of the effort to incorporate composites with airplane structures. To ensure the orderly development of structural composites and the transfer of knowledge from the Materials Laboratory to FDL and industry, an engineer was assigned full-time to the Materials Lab.

By the late sixties composites research had taken on enough importance to merit the creation of a special branch within the Structures Division. Because of their high strength and stiffness, composites are especially important for aerospace vehicles. Initial success with boron-epoxy systems encouraged research into filamentary and whisker reinforced composite systems with organic and metallic matrices. In 1975 the Structural Development Branch, jointly manned with the Materials Lab, became responsible for composites research; a year later the application of composite structures to the B-1 bomber was transitioned to FDL from the B-1 ADPO.

An example of an advanced composite wing.

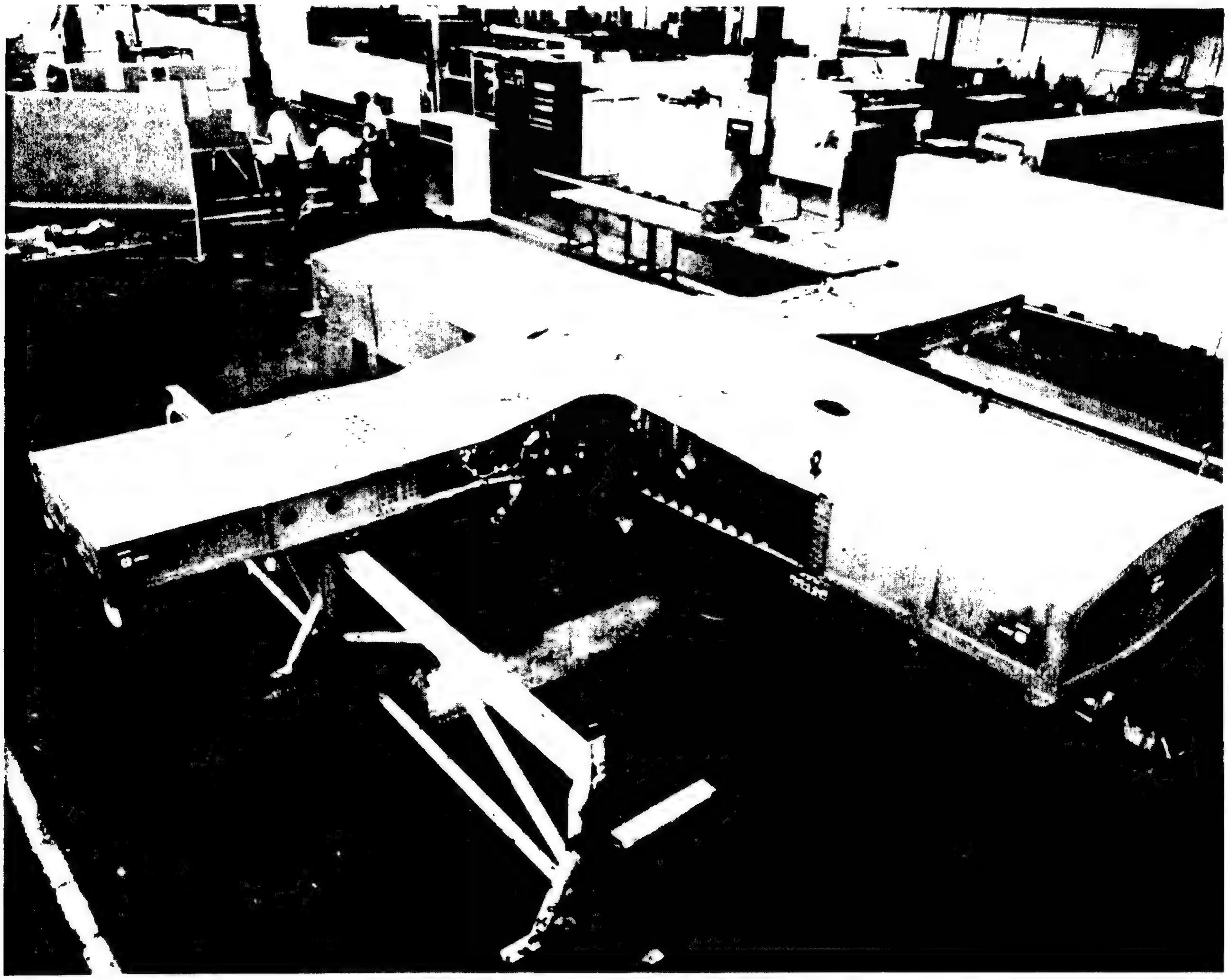


Model and scale component from the Advanced Metallic Structures (AMS) program.



This F-15 engine nozzle fairing demonstrated the feasibility of superplastic forming/diffusion bonding for intricately shaped structures.

In the late seventies a variety of materials and composites projects were initiated, including the Advanced Metallic Structures (AMS) program. An advanced technology missile shroud was developed, with a 31% weight reduction and significant cost savings. The first successful fabrication of a heavy wall Superplastic Formed and Diffusion Bonded (SPF/DB) titanium sandwich cylindrical tube section was achieved in 1980.



All-titanium conceptual wing/fuselage structure, manufactured by superplastic forming and diffusion bonding.

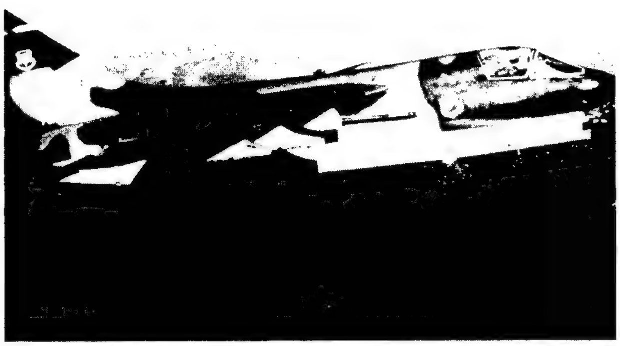
Superplastic formed aluminum bulkhead for the T-39 (lower left), compared with an old style bulkhead. The new bulkhead is cheaper and stronger.

A year later the Structural Concepts Branch had sponsored the development of a T-39 forward fuselage frame to test superplastic formed aluminum structures.

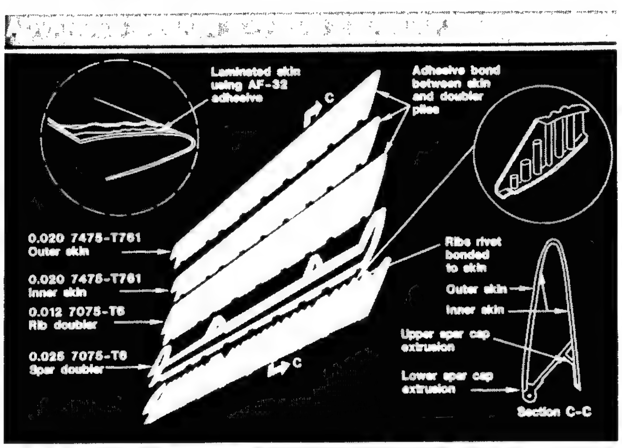
In 1978 the F-15 SPO contracted with the Lab to develop an SPF/DB nozzle fairing for the F-15 aircraft; it was successfully service-tested over a six-year period and led to further development of an SPF/DB aft fuselage for the F-15.

The MX missile program of the early eighties drew heavily on the Division's materials and structures expertise. A composite Deployment Module using graphite/epoxy was developed to replace the unsatisfactory aluminum deployment module. A weight savings of over forty pounds

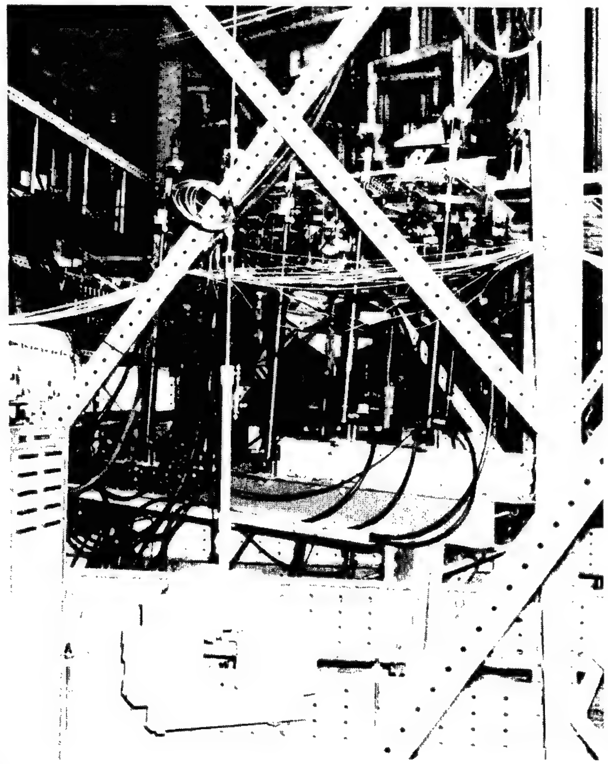
Advanced deployment module for the MX missile. The AMS program realized significant weight savings for the MX.



A-7 aircraft leading edges often experienced premature failures. The A-7D Composite Outer Wing Test Program was aimed at lowering the cost of replacement.



Newly redesigned A-7 leading edge.



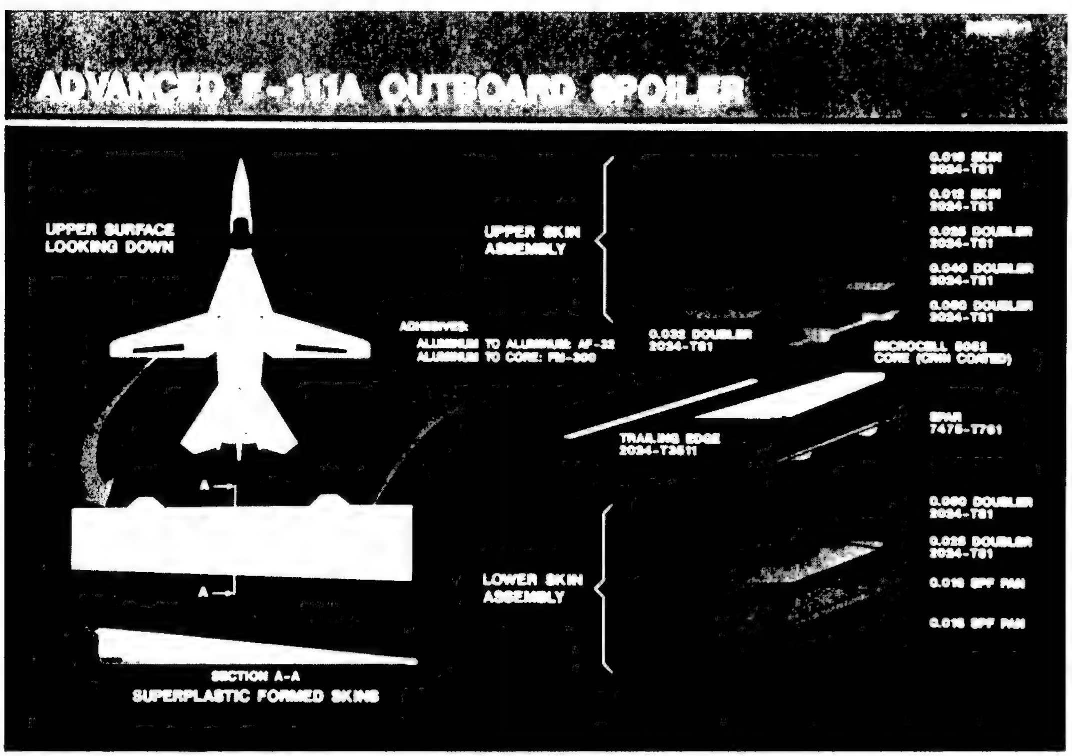
This A-7 composite outer wing survived over 16,000 hours of simulated flight loads at the Structural Test Facility.

and a 10% cost reduction were achieved. Later a complete substructure for the MX was built and successfully completed nuclear impulse simulation testing.

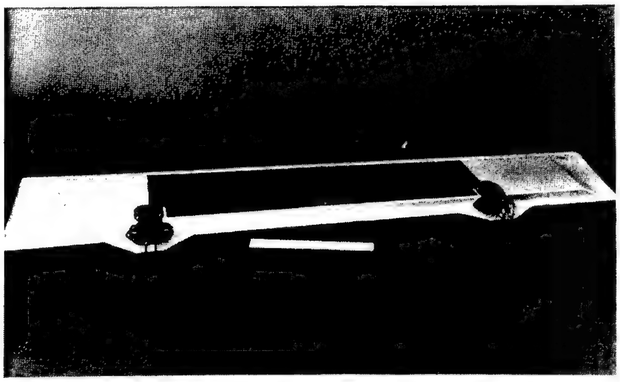
An A-7D Composite Outer Wing Test Program designed and tested a graphite and boron/epoxy wing structure capable of lasting through the entire 8000-hour life of the aircraft. The wing panel survived 16,000 simulated flight hours with no failures.

In 1982 the Division evaluated new techniques for patching cracked aluminum structures with composite materials. Composite technology is presently being applied to the development of a lightweight survivable integral fuel tank structure. Also in the mid-eighties the Advanced Composite Supportable Structures program, under contract with Sikorsky, explored innovative composite materials and designs for aircraft fuselages. Two rear fuselages were built and retrofitted to Air Force and Army HH-60A

F-111 spoiler, deployed on the upper surface of the left wing. The premature fatigue failure of these spoilers has been studied recently at FDL.



Technologies like integrally damped laminated skins, superplastic forming, sine wave ribs, rivet bonded assemblies, and advanced metallic structural materials were utilized in redesigning the F-111 spoiler.



The F-111 spoiler (here fully assembled) is now an Air Force preferred spare part, and saves more than $2 million a year.

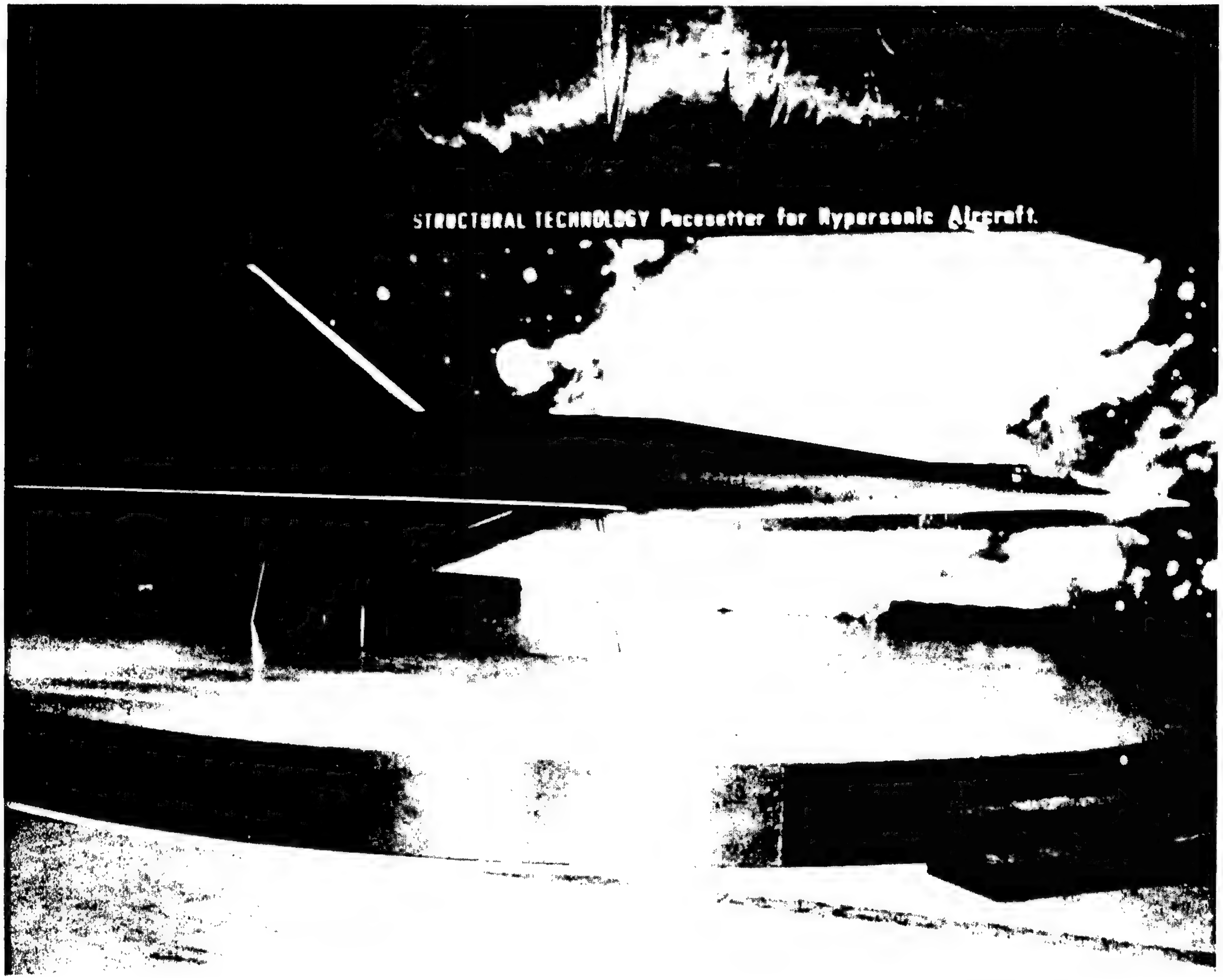
helicopters. The Army Blackhawk SPO also provided funds for construction of a third fuselage, to be ground tested for ballistic, electromagnetic, and lightning strike capability.

In 1987 the Structures Division demonstrated the application of carbon-carbon composites to two-dimensional exhaust nozzles for turbine engines. The components underwent structural and engine tests and were fabricated with oxidation-inhibited carbon-carbon substrates with protective coatings applied by chemical vapor deposition. A complete two-dimensional nozzle, consisting of two divergent flaps, two convergent flaps and two sidewalls, was assembled and tested on a J85 engine in the NASA Lewis Research Center. This was the first engine test of structural parts made with oxidation-inhibited carbon-carbon. The test components were the largest coated carbon-carbon nozzle parts ever produced, and made up the first complete structural carbon-carbon two-dimensional exhaust nozzle.

The Structures Division has significantly contributed to the certification process of advanced composite structures by sponsoring two technology development efforts: the Composite Wing/Fuselage Program and the Damage Tolerance of Composites Program. Both programs were needed, to fill a void in the structural integrity technology for composite structures and to permit a standard approach in certifying structures made of or containing advanced composites. The Wing/Fuselage Program determined the effects of various design parameters on the durability of advanced composite structures and used them to recommend a procedure to certify durability in composite structures. The results of the Damage Tolerance of Composites Program are the basis for establishing methods for the certification of advanced composite safety-of-flight structures. These efforts were concluded in 1988. They form the foundation to assure durability and safety of composite primary structures in Air Force weapon systems.

Facilities

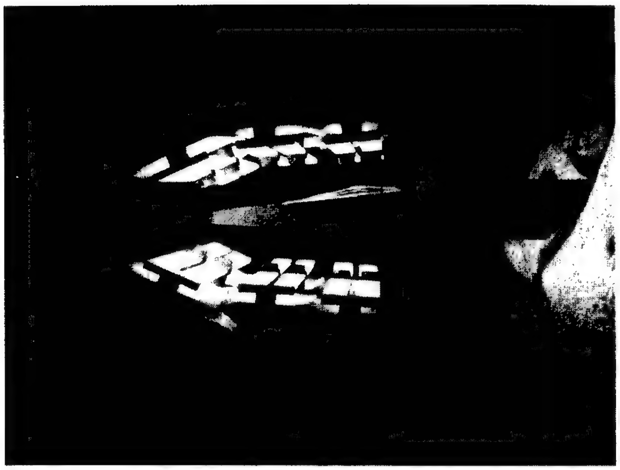
Structural testing was initiated at McCook Field to establish the adequacy of the airframe and to lower the risk of in-flight failures. For many years testing was conducted with the use of heavy shot bags and other inert deadweights to simulate various loads. Mechanical devices -- levers and screwjacks -- were employed to apply the loads When the Airplane Lab moved to Wright Field, structural testing was first conducted in the hangar-like Building 31. In the 1930s the Airplane Lab acquired a new range of facilities specifically built for structures testing. The Structures Laboratory was the proving ground for innumerable aircraft design techniques. The facility conducted static testing with shot bags and lead bars, and drop testing with a 52-ton jig capable of lifting any aircraft then made. Two overhead traveling cranes of five and fifteen ton capacity provided the lifting capability for the airframes and the test jig components. A small machine shop provided support and did minor repairs on test airframes. By the early 1940s this facility was no longer adequate for some of the new, large bombers then in the planning stage. A new array of test facilities was added during World War II and updated after the war as jet aircraft were developed. The current Structural Test Facility (Building 65, a Wright Field landmark) has been in operation site since 1944.



High temperature structures were being researched here long before the NASP needed them.

Building 65 became one of the earliest "modern" facilities with the addition of the Elevated Temperature Test Facility, completed in 1954. This was part of a major Air Force effort to improve test facilities; the Arnold Engineering Development Center in Tennessee dates from the same period. Originally a 3-megawatt facility (small enough that it could be moved to Arnold, if necessary) the Elevated Temperature Facility was so successful that ARDC gave the go-ahead for an expansion at Wright Field. It now operates with 50 megawatts and is capable of simulating either an equilibrium temperature condition to produce heating equivalent to the adiabatic wall temperature, or a "transient" or thermal shock condition in which the surface of the vehicle reaches a much higher temperature than the interior. The techniques developed at this facility have been widely applied by industry and the military.

The Titan, Thor and Hawk missiles and the fins of the Navaho missile were the first structures tested in the Elevated Temperature Facility, in 1956. Two years later the entire airframe of an F-106 was the subject of the world's first full-scale elevated temperature static test, and shortly thereafter a much larger B-58 was tested. In 1960 components built by Boeing and Bell were tested at the hitherto unattainable temperature of 2000F, and in 1964 the Thermantic Specimen Test Program achieved levels of 3200 degrees over a seventy-foot area.

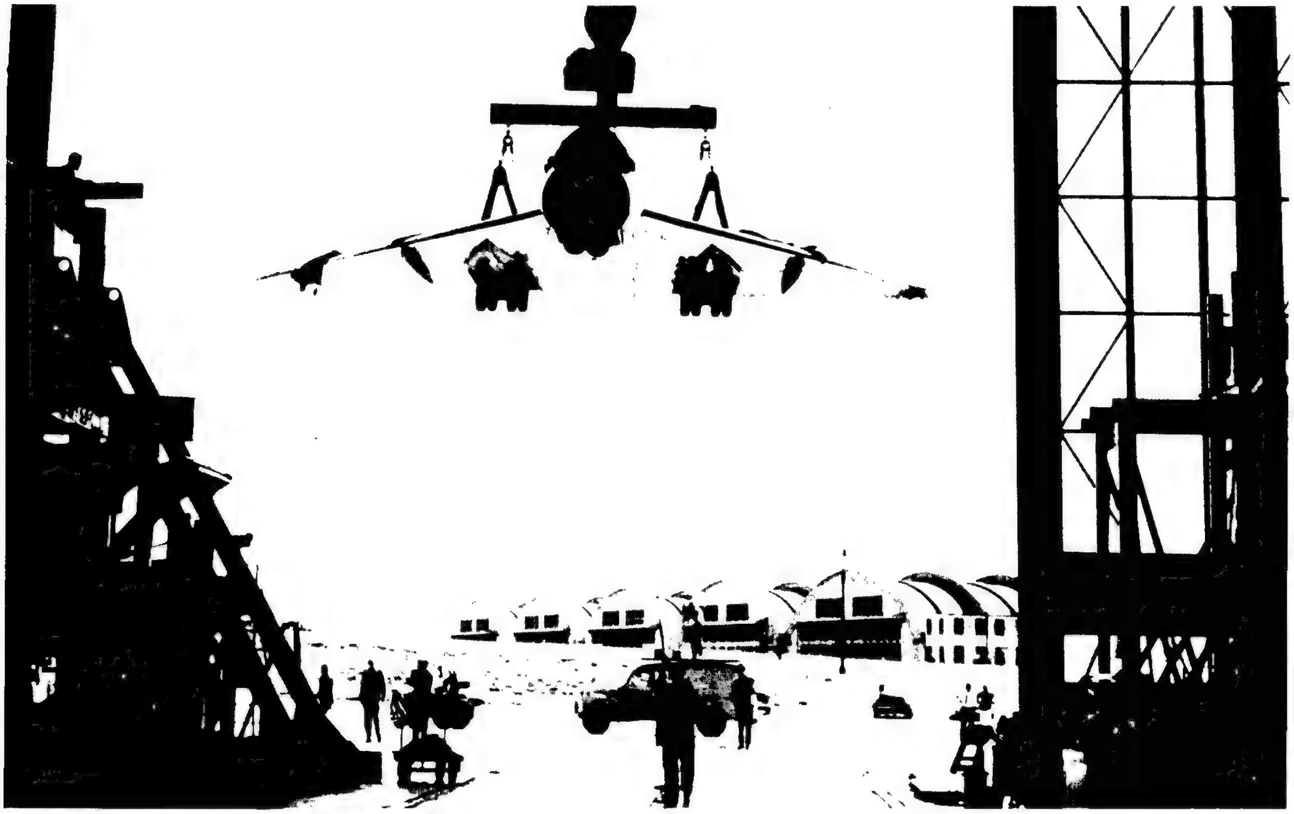


Modular graphite heaters have recently been added to the repertoire of high temperature test devices in Building 65. The 12 heater modules are arranged in groups of four to provide three heating zones on this generic graphite leading edge structure.

Engineers and technicians need eye protection while witnessing this X-20 high temperature test.

This program used a ceramic-coated structure over a high-temperature metal honeycomb filled with ceramic foam and an inner aluminum water-cooled section, designed to test criteria for lifting-body re-entry nose cones. The facility had completed preparations to test the X-20 Dyna-Soar before that program was cancelled.

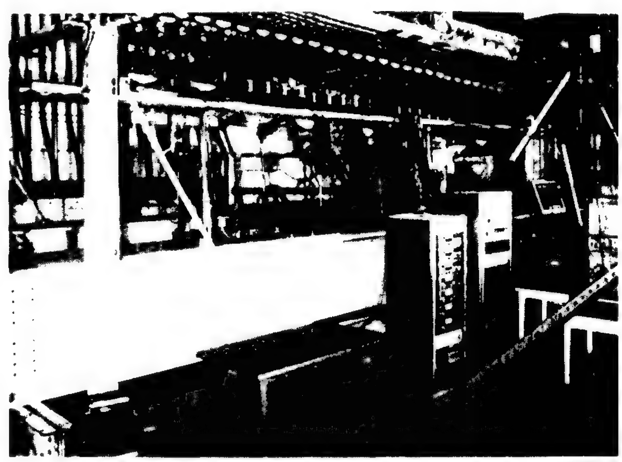
Aircraft for structural testing have arrived at Building 65 by air, truck, and rail, and have even been towed down Route 444 from Patterson Field. This B-58, with tail removed, was tucked into the bomb bay of a B-36 and flown in (1957).



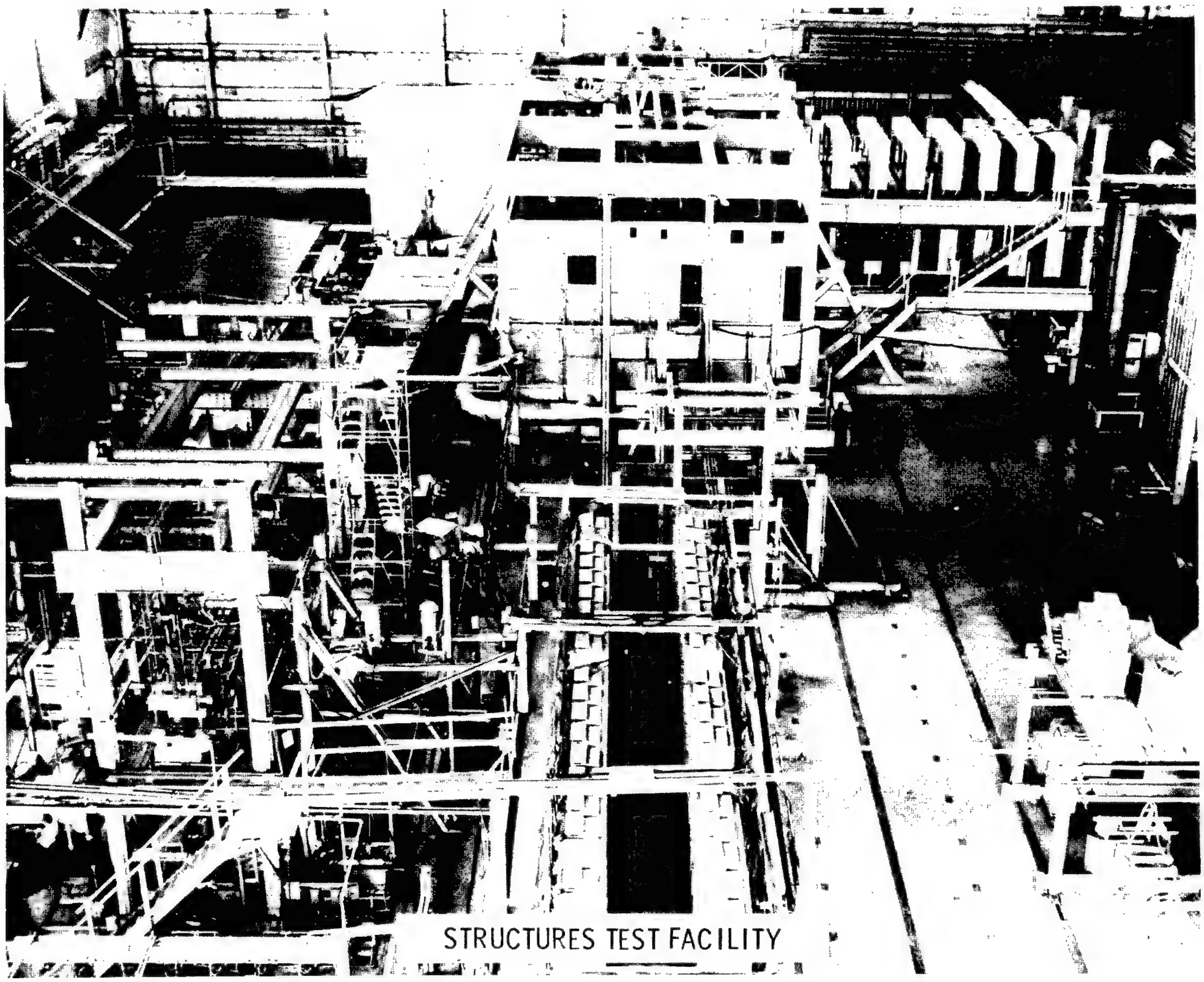
The B-58 is brought into Building 65 by large overhead cranes.

By about 1970 most high-temperature testing for hypersonic applications had ended, as the Vietnam conflict and other weapon systems needs took priority. Not until the late 1980s, when the National Aerospace Plane program got under way, was the Elevated Temperature Test Facility employed to anything approaching its full capacity. Plans are now under way to add new modular graphite heating units that can produce temperatures in excess of 4000F.

The Convair B-58 was the first full-scale aircraft tested at elevated temperatures with actual fuel in the tanks.



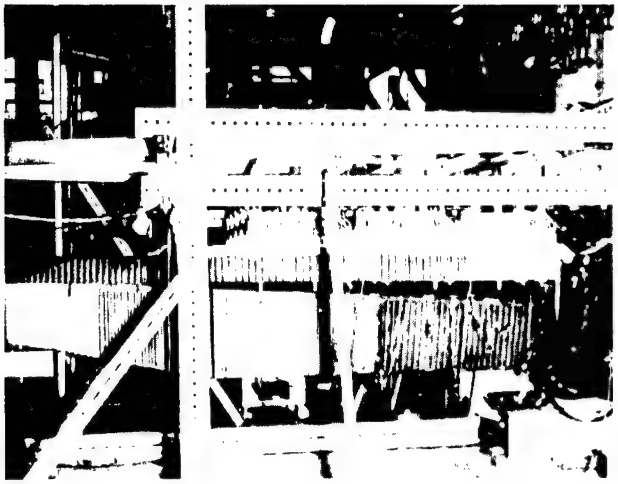
YC-15 wing, typical of the composite, metallic and hybrid structures tested in Building 65.



Equipment in the Structural Test Facility is continually updated and upgraded to accommodate advanced test techniques and requirements.

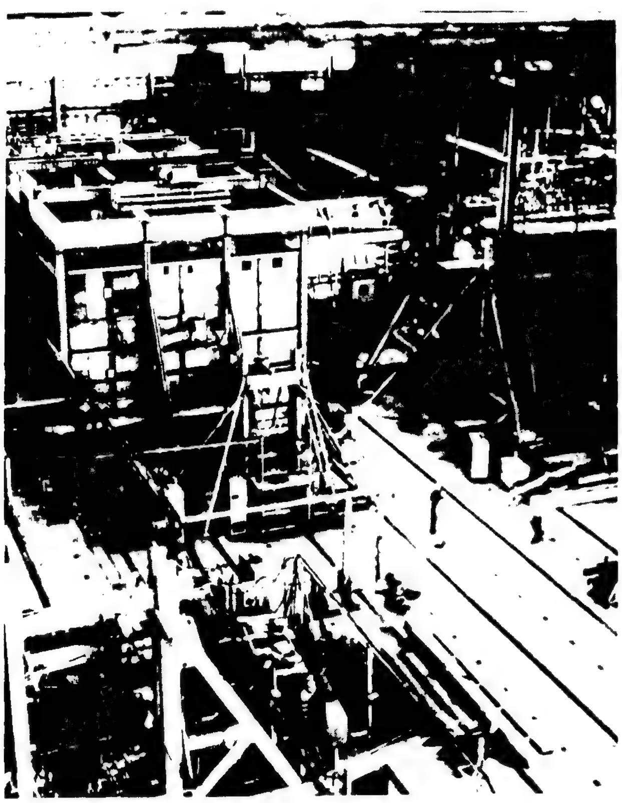
In addition to heat testing, the Lab in the fifties pioneered in the utilization of bonded rubber tension pads, which could be adhered to any part of the aircraft for better distribution and more complete hydraulic setups. When the need arose to test supersonic and hypersonic structures at high temperatures, the Lab's engineers developed silicone-bonded metal tension pads which could tolerate temperatures of up to 550 degrees F. It should be noted that Capt. Paul Kemmer (first Aircraft Lab chief) and engineer Ed Weaver received the first patent for a tension patch loading device.

In the early sixties the Structural Test Facility included three major components, which specialized in thermal stress, loads, and cryogenics. The Radiant Heat System had 50,000 KW of power, computer-controlled to be programmed as heat flux density or time-temperature, both on real-time basis. The temperature simulation range was 150 to 3000 degrees F on large surface areas. The Basic Load Applications Systems facility utilized a wide range of hydraulic cylinders which could be controlled either manually or through an automatic system. The heart of the Data System facility was the High Speed Data Acquisition System, a time-shared commutated system with 1928 channels and a maximum sampling rate of one hundred samples per channel per second.

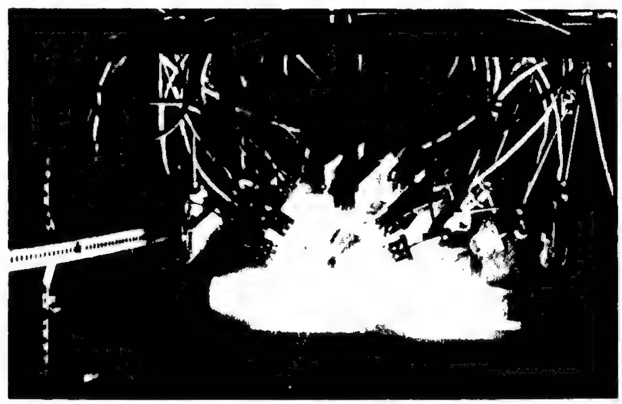


Test of a developmental structural configuration of a lifting re-entry body. A programmed load is applied at a temperature of 2000 degrees Fahrenheit.

Building 65 computer room. Many data channels are available for monitoring all test parameters.



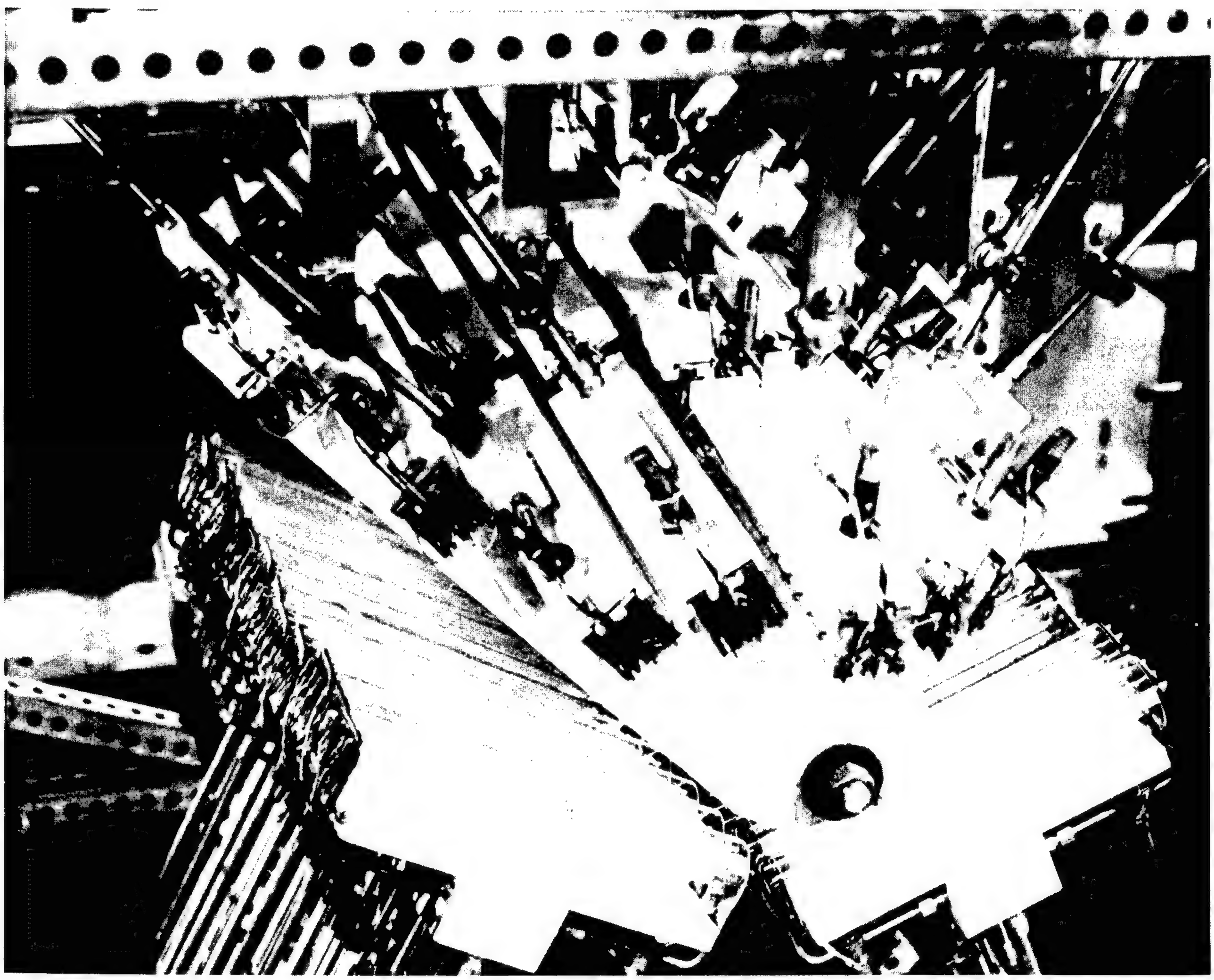
This cryogenic test facility can test many components and, in some cases, full scale vehicles operating in the spectrum from V/STOL through orbital re-entry missions.



Advances in materials and flight technologies have created new requirements for high temperature testing of re-entry vehicle structures. Hypersonic test specimen, Building 65.

The advanced cryogenic test area was added to this facility in 1965. It operated over a range of -320 to 3000F, utilizing a 10,000 gallon liquid nitrogen tank. The facility was capable of testing any component and some full-scale vehicles operating across the spectrum from V/STOL to orbital re-entry.

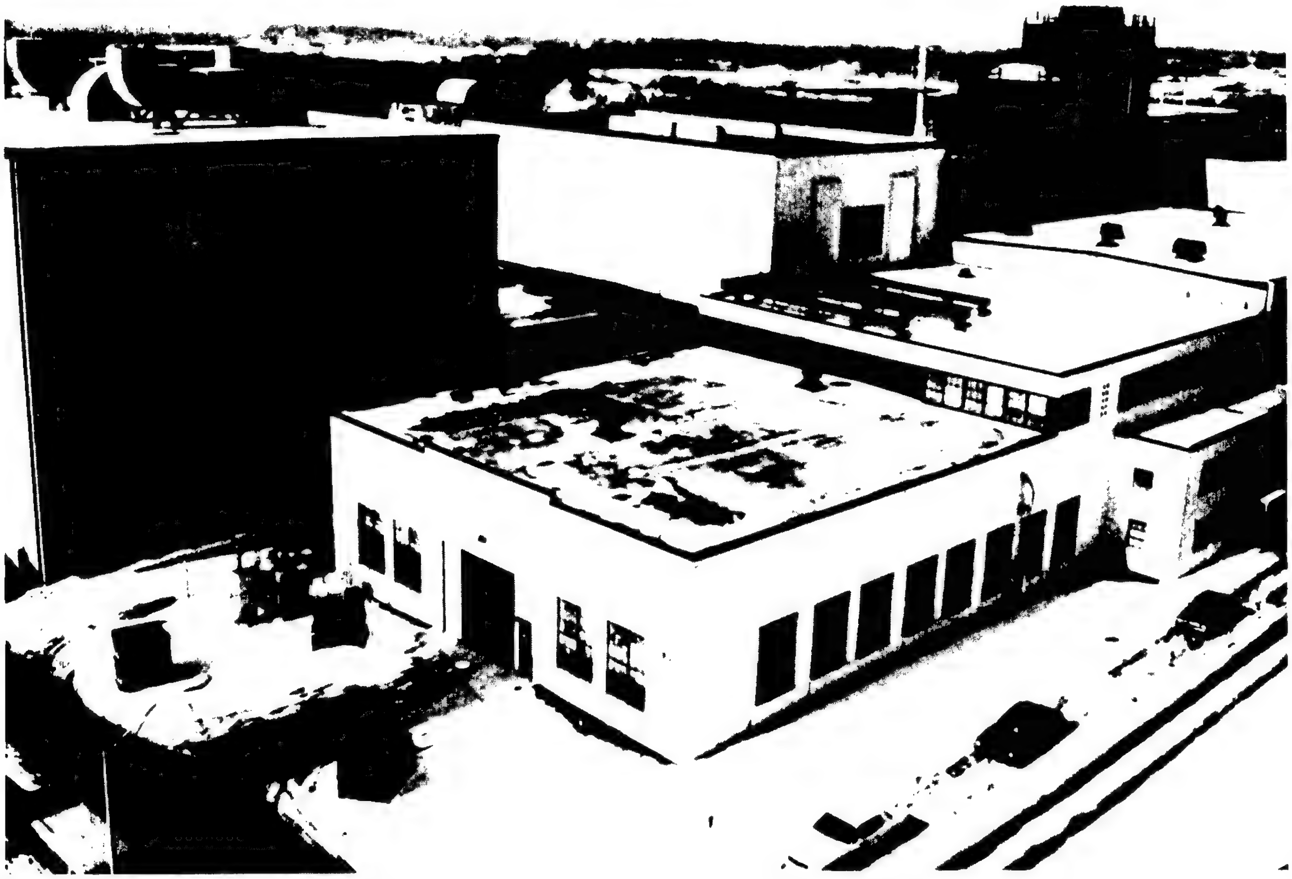
The Structural Test Facility continued to grow in the 1970s, adding the capability to perform a full range of tests from basic evaluation of



These T-3 quartz lamps can provide limited sustained temperatures up to 2700 degrees Fahrenheit and peak flux rates of 150 watts/cm^2.

fracture and fatigue characteristics of joining techniques, through intermediate scale testing of conceptual structures and subassemblies, to full-scale testing of flight vehicles. The new Structural Mechanics Division took responsibility for the test facility in 1975, and during the late seventies it was involved in the AMAVS, CAST and many other projects, including the design of advanced external tanks. Currently the facility is working on a method of spray-coating the interior of fuel tanks, to replace the standard bladder and thus eliminate many of the leakage problems which have plagued high-velocity aircraft. Testing of actively cooled hypersonic nose cones and leading edges is also

Advanced Vortek heater, showing heater element and focusing apparatus, with cooling lines in the background.



Buildings 24B and 461 housed acoustic and vibration test equipment.

under way, and the facility is working on a new low-cost graphite heater capable of heating small structures to temperatures of 4000F or better. The recently developed Vortek arc lamp will be used to test nose cones and leading edges at similarly high temperatures. McDonnell and General Dynamics are the major contractors for this work.

The Future of Structures Research

Since the 1950s structural engineers have recognized the trend toward hypersonic aerospace vehicles, and much of the research conducted in the past three decades will have contributed to the eventual success of the National Aerospace Plane. The ill-fated Dyna-Soar was the first effort in this direction, and though the X-20 never got off the ground, the program contributed to the technology of NASA's space program. Thermantic structures, the Advanced Structures Concepts Experimental Program (ASCEP), and other projects kept hypersonic vehicle research alive through the seventies, though they did not receive enough funding to allow for major advances. Today this field is again expanding rapidly. "I waited twenty years for hypersonics to come back," says Sanford Lustig of the Structural Test Facility, "and it finally did." When the National Aerospace Plane takes off sometime in the 1990s, the structures engineers of the Flight Dynamics

Lab will bear a major part of the responsibility for its success.

In addition, structures research will continue to focus on heat transfer studies and on the development of improved computer programs to predict the effects of loads and stresses. Advanced fighter aircraft, which maneuver at high velocities and angles of attack, are an area of particular concern. Use of the Navier-Stokes methods with a moving aircraft is a goal for the mid-1990s as an advanced method of predicting flight loads. The Lab is also assisting with the solution of structural problems in the space-based laser concept within the SDI program.

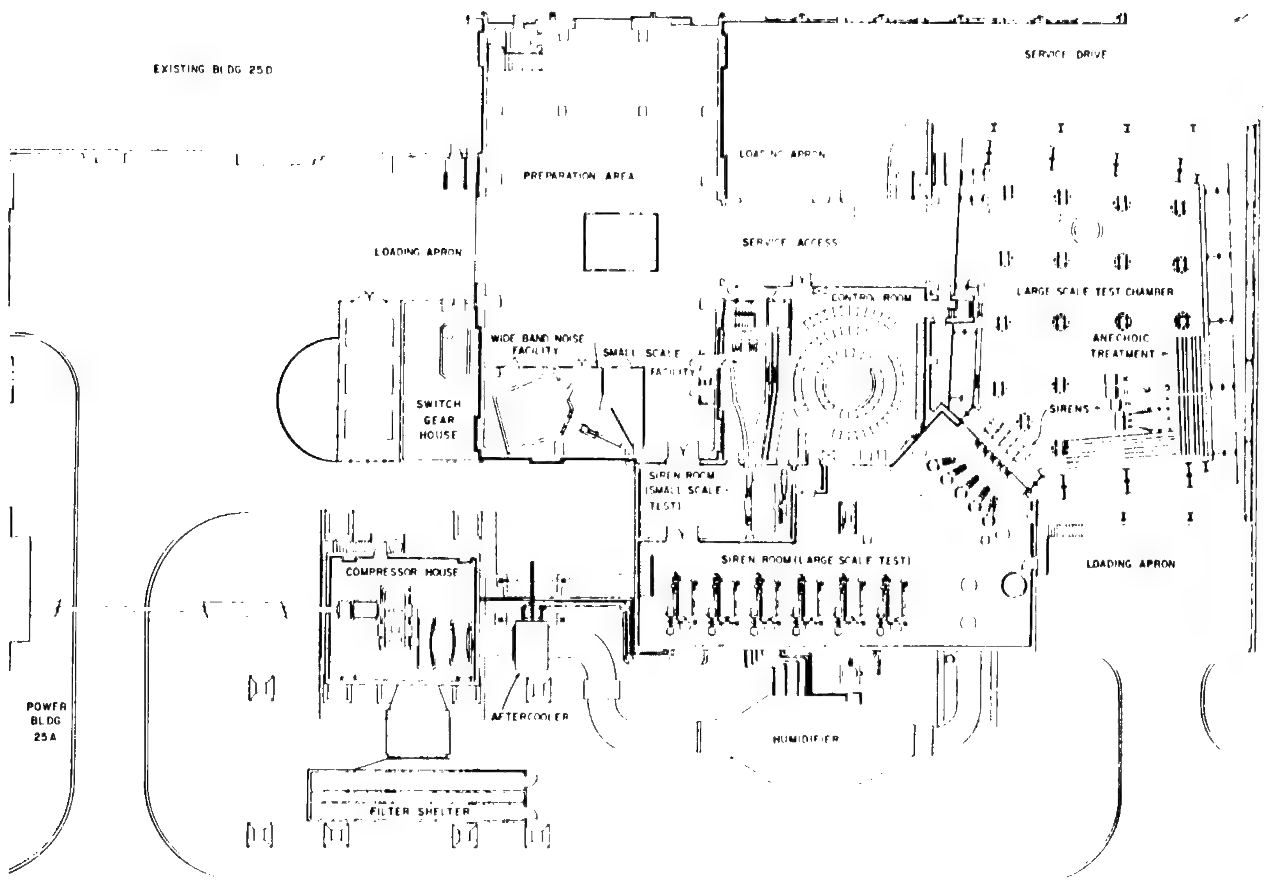
VEHICLE DYNAMICS

Dynamics has been a fundamental factor in aircraft design since the days of the Wright Brothers. However, the short duration and low power requirements of their early flights did not foreshadow the dynamics problems that would later emerge. Since that time dynamics has come to be defined as the study of acoustics, vibrations, dynamic loads, aeroelasticity and other airframe dynamic stresses. The field deals with motions and loads which are highly time dependent, that is, where motion and load magnitudes vary sufficiently to prevent considering them as static conditions. Resonance is a particular concern of dynamics research because it magnifies the stress or motion many times and leads to component failures which would not occur under static conditions. The Flight Dynamics Lab has conducted research into all facets of the field. Aero-acoustics, vibration and flutter, which have usually been the responsibility of a Vehicle Dynamics branch, continue to be a major contribution of the Structures Division. In the mid to late 1940s aircraft dynamics was the responsibility of the Aircraft Lab's Dynamics Branch. Howard Magrath, who retired in 1976 as chief of the Vehicle Dynamics Division, was first chief of Dynamics after the reorganization of the early fifties, and a recognized pioneer in the field. This branch prepared handbooks and specifications, and conducted research and experimental programs to validate engineering predictions or discover errors in manufacturers' work. Military specifications and handbooks are the basis for procuring future aircraft; therefore, it is essential that they accurately reflect the state of the art. Considerable time and effort went into these tasks.

The Vehicle Dynamics Division's Aerospace Dynamics Branch, which existed from 1965 to 1976, originated or contributed to a wide variety of advanced concepts, including Project ASSET, STOL technology, the AFTI/F-16 project, the TACT program, the X-24A and B, the Mission Adaptive Wing, and (after the dissolution of the Prototype Division) the miniature remotely piloted vehicle. Development of the hypersonic glide vehicle, which is now undergoing a revival as the National Aerospace Plane project, had its origins in the Aerospace Vehicle Branch and the Aeromechanics Division.

Acoustics

Since McCook Field days the Airplane Lab and its successors have worked on acoustics problems arising from propulsion systems (both propeller and jet) and flight through the atmosphere. Sonic fatigue, the weakening of structures by sound waves, became a critical problem as propulsion systems grew in power. Though sonic fatigue does not usually endanger human lives, it can be costly in terms of structural failures, maintenance cost and mission effectiveness. It is virtually unpredictable, and for many decades defied attempts to establish precise design and prediction parameters. Propeller engines create a harmonic excitation over a narrow frequency range, which leads to sidewall failures but is relatively easy to correct. Jet engines produce a random noise across a much wider band, which can excite further resonance problems. Since jet aircraft travel faster, noise from the aerodynamic boundary layer is also more intense. These types of noise, sustained at a high level over long periods, result in crew fatigue and poor verbal communication. Working with data supplied by the Bio-Medical



MAIN FLOOR PLAN, SONIC FATIGUE FACILITY

The Sonic Test Facility contains a wide band noise facility, a large scale test chamber, and several small scale siren rooms.

Lab, FDL during the 1950s tested and improved a wide variety of soundproofing methods. Materials such as fiberglass proved useful in noise alleviation.

When the Aircraft Laboratory (as part of ASD) began acoustics research, a number of prediction studies were conducted, resulting in methods for predicting propeller and aerodynamic noise. WADC TR 58-343, Volume I, was the standard reference on these noise prediction methods. It was soon outdated, however, as aircraft using jets and rockets reached higher Mach numbers. Separated flow, oscillating shocks, and base pressure fluctuations were a few of the new sources of noise that emerged at higher performance levels. Millions of dollars were being lost to acoustic fatigue failures in the Snark missile, the KC-135, the B-36 and other aircraft. A second volume of TR 58-343, issued in 1960, contained methods for predicting many of these noise sources, and design procedures for preventing sonic fatigue. Both manuals have served the developing technology well, by providing vital standards for designers.

The Dynamics Branch was also responsible for measuring, specifying, and controlling aircraft interior and exterior noise which was of sufficient intensity to interfere with crew communications; field measurements of ground noise levels around aircraft structures were conducted. The Branch also studied helicopter rotor-induced vibration which could negate isolation methods and interfere with crew comfort. A particular helicopter problem was the coupling of rotor and fuselage vibration modes, which could produce an instability powerful enough to destroy the

Engineer inspects the termination chamber of one of the small sonic fatigue facilities used in the mid 1960s.

helicopter. O. R. Rogers was the chief of this group.

At times, acoustics studies have made major differences in the configuration of experimental aircraft. During the development of the X-21, designers found that jet noise could trip the laminar boundary layer and cause turbulence, thus negating the beneficial effects of laminar flow. As a result the engines had to be moved from under the wing to the rear of the fuselage in order to reduce the level of noise on the wing surface.

In the 1960s work continued on the noise aspects of the boundary layer. Another major concern of the time was the measurement of ground noise levels of overflying aircraft, to predict their detectability in combat arenas. Under the aegis of the Aero-acoustics Branch, sonic fatigue and noise control became prime areas of concentration. Facilities were established to produce controllable sound fields around test specimens and to create other environments such as low-frequency vibrations, heating effects and static loads. The Lab has pioneered in measurement techniques in this type of facility.

Though the Division's test facilities are today considerably more sophisticated than those in use in the 1960s, the original facilities were the most advanced of their time. The Large Sonic Fatigue test facility was built to accommodate vehicles up to the size of fighters and small missiles, and to perform tests at sound pressure levels up to 162 decibels. The large test chamber measured 42 x 56 x 70 feet and could be operated in a

Sonic Test Facility, Building 461, control room.

progressive wave or reverberating mode. Sound was generated by 35 discrete frequency sirens with a frequency range of 50 to 10,000 Hertz (cycles per second), and with a limited capability to produce random jet engine-type noise. The maximum acoustic power generated was one million watts. Seventy-two channels of data could be recorded simultaneously; by commutation of a number of channels, up to 342 transducer outputs could be recorded. In the mid-sixties the facility used an IBM 7094 digital computer to analyze these data.

The Small Sonic Fatigue facility, still in use, can accommodate small test specimens, usually models, in either a 1 x 1 or a 7 x 7 foot space. A decibel level of 174 can be achieved at a

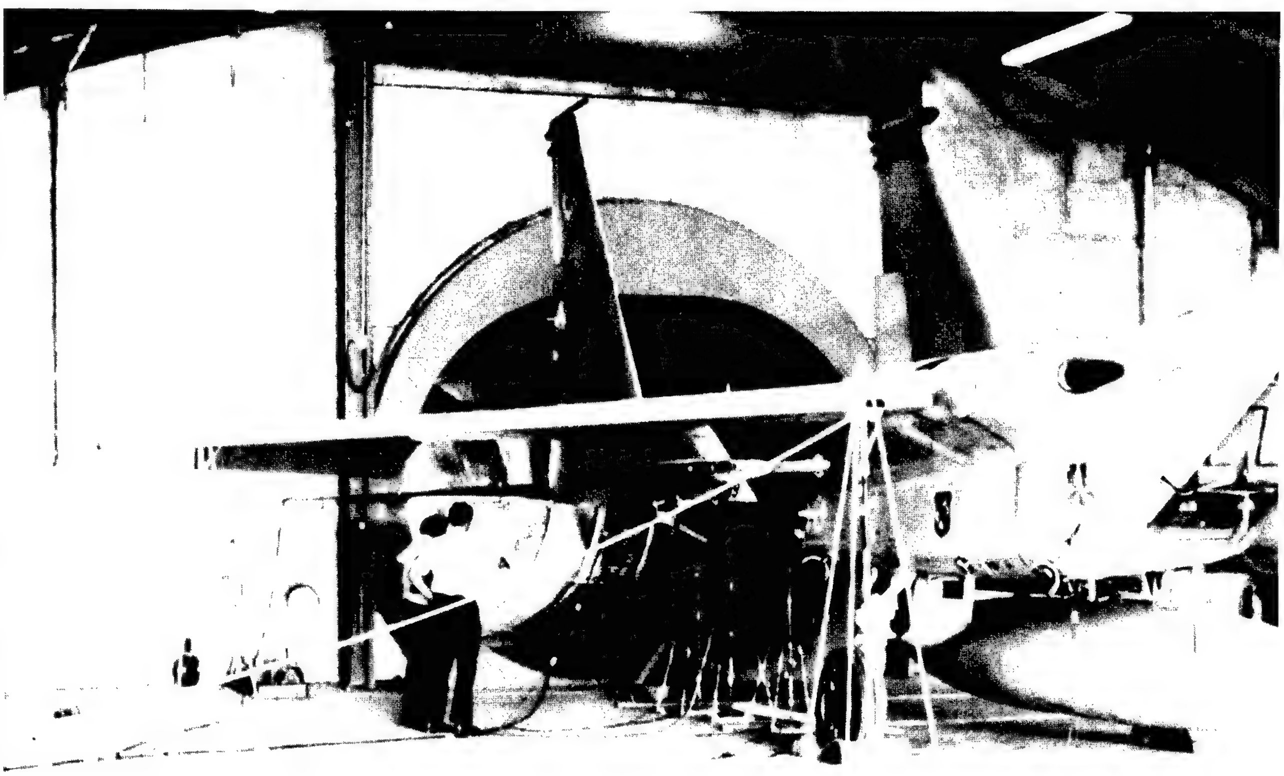
Advanced air-to-air missile, tested for sonic fatigue in the main chamber of the Sonic Test Facility.

maximum acoustic power of 50,000 watts. Data is recorded through twelve channels. One of the more successful programs carried out in this facility involved the prediction of sonic fatigue failures in the C-141, saving a great deal of money in retrofitting and maintenance.

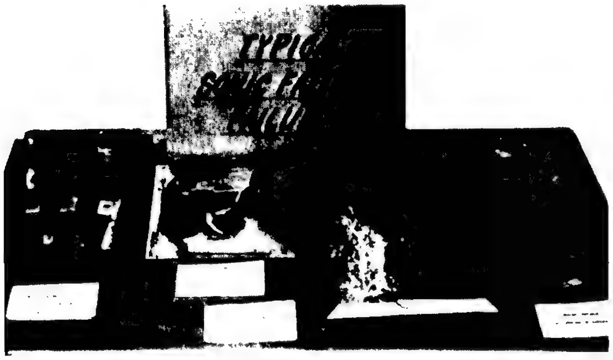
The Wide Band Noise facility uses a sound generator with a continuous frequency spectrum range from 50 to 12,000 Hertz. The facility is used particularly for testing electronic equipment. The test chamber is 19 x 10 x 8 feet, and the 11,600 watt sound generator can achieve a 166 decibel level.

Both of the sonic fatigue facilities at Wright Field were modelled on the High Intensity Acoustic Test Facility at Cambridge, Massachusetts, used to test electronics, materials, and substructures at sound pressure levels up to 175 decibels. The 25,000 watt generator operated in a frequency range of 20 to 10,000 Hertz.

In 1976 Vehicle Dynamics merged with Structures to form the Structural Mechanics Division. Acoustics research continued in the Structural Integrity branch. In the late seventies a major effort was directed at determining the sonic fatigue life of graphite-epoxy skin stringer panels when exposed to high intensity acoustic excitation. This analytical and experimental program was aimed at determining the elusive factors that determine random fatigue failures. The test rig consisted of a range of multi-bay

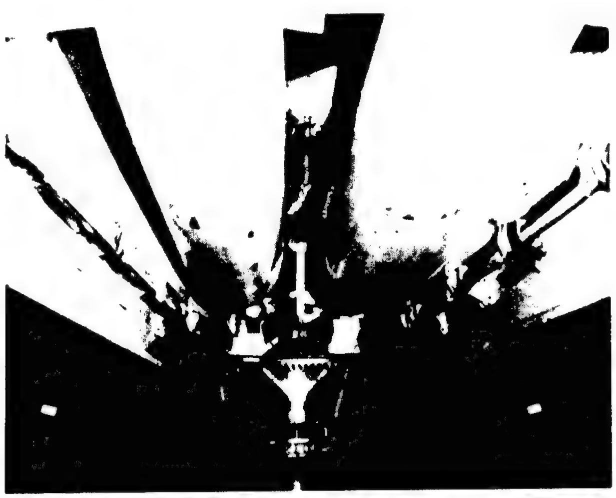


Lab acoustics engineers are sometimes called on to solve field-related problems in structures like this engine check-out cell.



Sonic fatigue can be a serious problem, as seen in the structural failures of these components.

This F-111 internal bay fence controls aero-acoustic flow.



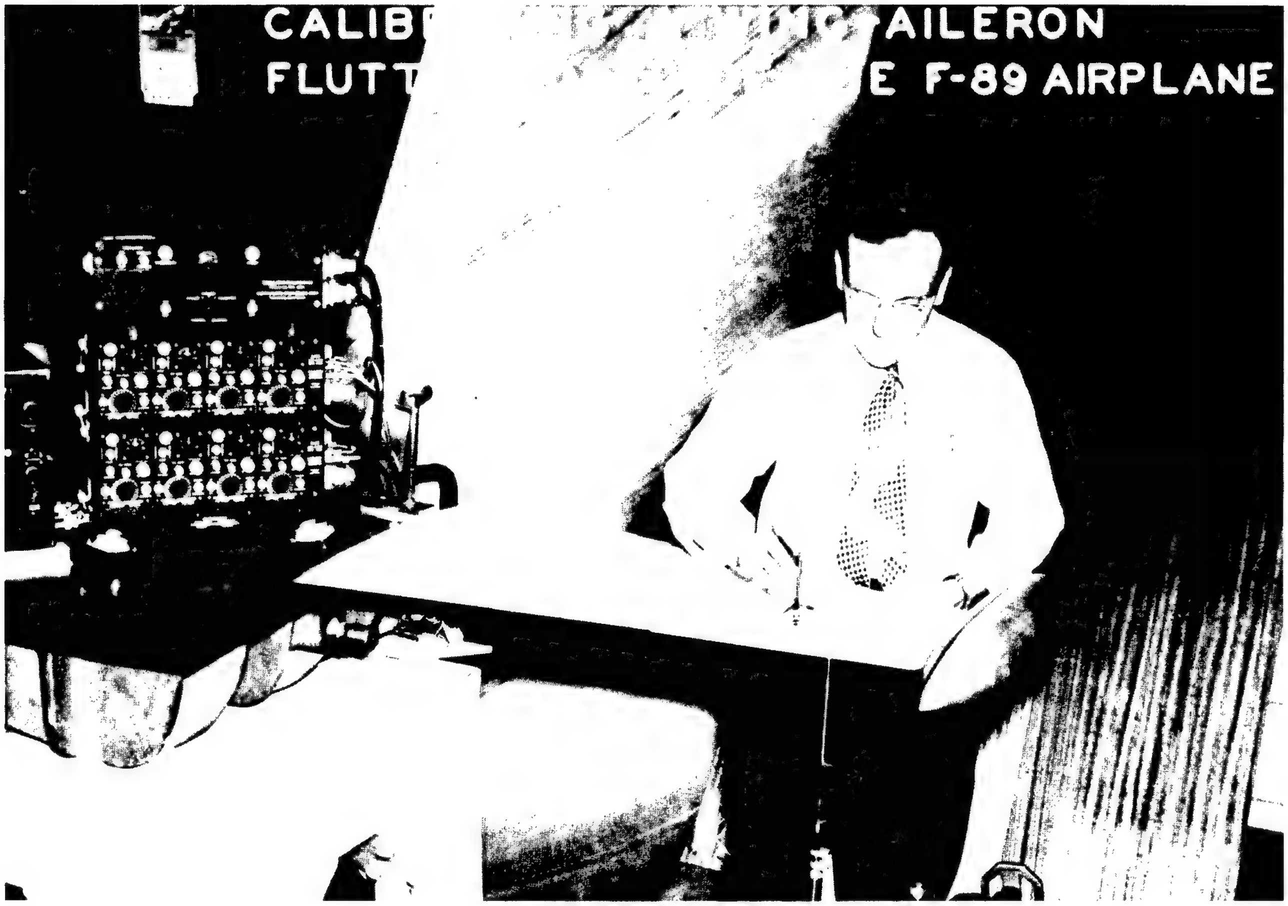
F-111 weapons bay with acoustic noise suppression device.

panels subjected to high intensity noise environments in a progressive wave tube. Finite element analysis and multiple stepwise regression analysis indicated that graphite offers a 2:1 weight savings over aluminum in panel construction, and a vast array of new sonic fatigue prevention data was acquired.

An acoustics measurements program was conducted in 1980 to determine whether hush house noise suppressor systems exceed the structural acoustics design limits of some aircraft and engines. A hush house is a sound chamber in which acoustic stresses strong enough to affect internal structures can be generated. Success was achieved with the F-15, F-16, and F-4 aircraft, and with the F100-PW-100 engine. No sonic fatigue problems were discovered with these structures operating; the practical result was substantially lower maintenance costs. Another suppression method was explored when the aero-acoustics group participated in a joint effort to extend the structural life of the F-4 airframe. In 1981 the group supported an investigation of cavity oscillation in cruise missile carrier aircraft, proving that a severe acoustic environment would be generated in transport aircraft modified as cruise missile carriers. Prediction methods were refined and some acoustic suppression methods were tested. The findings also had applications to conventional weapon bays and other cavities such as wheel wells and antenna windows.

Aeroelasticity: The Problem of Flutter

The most significant aeroelastic problem is flutter: an instability of the aircraft leading to failure, which may manifest as divergence, panel flutter, or gyro flutter, among others. The importance of flexibility on "aeroelastic response" of aircraft components and on flight safety was recognized very early, and pioneering research was conducted at McCook Field as early as 1922. During the 1930s several flutter problems with control surfaces were identified, and the Army Air Corps design handbook was updated with flutter data obtained in tests with



Early flutter work was conducted on scale models. This F-89 aircraft is being calibrated for a wing-aileron flutter test.

the 5-foot wind tunnel. Ground vibration, control surface flutter, flight flutter, and flutter model tests were conducted at Wright Field just before World War II, and results were published as TR 4798. A Flutter and Vibration Section was created in the Aircraft Lab in August 1939. Most of the section's testing had to be done in flight, because wind-tunnel engineers would not permit testing of flexible models that might break up and damage the tunnels. The Lab continued to accumulate flutter data throughout the war years and several technical reports were issued. Advances in the early 1950s brought the subject into greater prominence. High-performance jet aircraft might have been expected to develop more serious flutter problems, but the design groundwork already performed at the Lab prevented most of these. Only about twenty cases of flutter occurred in new aircraft between 1952 and 1956.

Much of the pioneering research on flutter was conducted by L. Wasserman, I. Spielberg, Walter Mykytow and others. Standard test methods (such as the use of isolation mounts) were also pioneered at Lab facilities. The Dynamics Branch in the 1950s established design criteria for flutter prevention on wings with control surfaces involving stiffness and free-play requirements, all-movable tails, and T-tails. These criteria became MIL-specs and were invaluable to the Air Force and Navy in the development of the Century series fighters and other aircraft. These specs were also basic references for many foreign military and civilian aircraft. As Walter Mykytow recalls, during his 36 years at the Lab (1939-1975) "there were

The FDL Active Flutter Suppression program has evaluated several concepts for the alleviation of wing/store flutter in fighter aircraft.

Mounting stores on the wings can significantly reduce flutter speeds, although modes change when stores are separated.

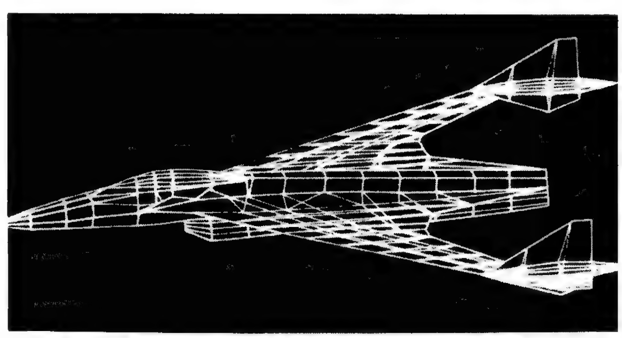
50-60 flutter incidents/accidents. Only a few (2-3) were violent or resulted in loss of aircraft. That is a damn good record."

High velocity aircraft require wings and bodies that are much thinner, and therefore more flexible, than those of earlier airframes. As these vehicles were developed, a variety of flutter problems emerged. The Aircraft Lab was given responsibility for solving these unprecedented problems. In the early fifties a way was found to prevent T-tail flutter on the Matador missile, and the problem was eliminated in the F-104 by increasing the rigidity of the scissors. These studies led to further explorations in the field of aeroelasticity. By 1955, when the Lab began in-house construction of flutter models, engineers established design criteria and procedures to prevent all-movable tail flutter and the effects of engine and cargo mass on flutter. The transonic regime presented special flutter problems, and the Dynamics Branch successfully defined preliminary methods using the results from transonic flutter model tests.

On the theoretical side, many analysis and prediction techniques have resulted from these aeroelastic studies. For example, practical engineering methods were developed for applying the subsonic kernel function and the supersonic Mach box, essential for the design of high speed, low aspect ratio surfaces such as the wings of the F-102, F-106 and B-58. Also the need for a reliable transonic unsteady aerodynamic theory was identified. In 1958 the Lab explored "piston theory" for predicting unsteady aerodynamic pressures at high Mach numbers, and by 1962 wind tunnel tests had shown that the theory held promise. Some shortcomings in prediction of the center of pressure were encountered, but the X-15 and other experimental craft benefited immediately from this advance. The technique was later applied to Scramjet design. Working through contractors, the Lab also sponsored the discovery of the doublet-lattice subsonic method, replacing the old isolated wing "strip method" of predicting aerodynamics for flutter analysis. The doublet-lattice, which accounts for interference between surfaces so that subsonic flutter analyses can be made, has become the worldwide standard in aircraft design.

During 1962 and 1963 the Branch conducted tests on panel flutter, which was a serious problem with certain supersonic aircraft. Panel flutter prediction methods were developed, and have been widely used for supersonic vehicle design. Funding provided by the FAA allowed research on panel flutter in the proposed Supersonic Transport (SST). Soon the reorganized Vehicle Dynamics Division tackled the special difficulties encountered during re-entry in control surfaces on advanced lifting body configurations. Wind tunnel tests revealed the additional rotational stiffness required to prevent shock/boundary layer coupled instabilities, and these data were used in the design of Scramjets and recoverable boosters.

The emergence of radically new fighter designs in the early seventies uncovered unexpected flutter problems. As wing sweep was increased to 60 degrees, flutter occurred within predictable limits. But for wing sweep beyond 60 degrees, flutter speed dropped rapidly to values lower than those found in the lowest sweep position. This sharp reduction could have negative effects on aircraft performance. Tests were conducted in the AFIT five-foot subsonic wind tunnel and in the transonic wind tunnel using flutter models, and the engineers successfully delineated analysis and design



The increased wing sweep angles of fighters designed in the 1970s created new problems in flutter analysis.

The flutter suppression system on this quarter-scale F-16 model was successful at velocities beyond the unaugmented flutter boundaries.

criteria to prevent the phenomenon. One of the major breakthroughs of the mid-seventies was the exploration of methods in the transonic range, conducted by Magnus and Yoshihara, among others.

The more sophisticated aircraft systems of the 1970s used feedback to control for flutter and vibration. Since that time, aerodynamics and flight control engineers have worked together on the flutter problem: a good example of the "cross-pollination" that often occurs between different divisions of the Lab. Structural engineers therefore had to learn to integrate their technologies with flight control systems. "Aeroservoelasticity" was the name given to this new discipline, as servomechanisms were built into vibration-prone structures. Much of the initial work in this field was accomplished in the YF-16 test vehicle.

In cooperation with NASA Langley, the Vehicle Dynamics Division launched an effort in 1972 to develop technology to test active flutter suppression models in wind tunnels. As different stores (such as bombs or external tanks) are added to wings, the aerodynamics change and flutter can become a problem. The later stages of this work were continued by the Analysis and Optimization Branch, after the two divisions were combined in 1976. The purpose was to correlate reduced-scale flutter suppression

models with actual flight test results. A B-52 model was modified to include an active flutter suppression system similar to that in the CCV flight test vehicle. Wind tunnel test results from Langley were compared with flight test data. In 1978 the Lab undertook a joint investigation of flutter suppression with the Federal Republic of Germany. Wing/store active flutter suppression was demonstrated through flight-testing an F-4, which carried weights to deliberately create flutter. The Lab provided control surface actuators for the project. Methods were delineated for increasing flutter boundaries by as much as 30%.

In another program, the Division sponsored a flutter suppression system design study for an aeroelastically tailored HiMAT (highly maneuverable aircraft test) vehicle. Similar wind tunnel programs investigated servoelastic flutter control problems which emerged in the F-16 and YF-17, as additional bombs and stores were added to the vehicles.

Aeroelastic research continued under the auspices of the Structures Division after the 1975 reorganization. Unsteady aerodynamic methods for flutter prediction were further developed during the late seventies. Under Lab sponsorship the TSO computer code had already been initiated by Mike Shirk and Walter Mykytow for aeroelastic tailoring of composite structures for improved maneuverability, flutter and divergence. This code triggered a number of theoretical and hardware design studies. FASTOP (Flutter and Strength Optimization Program) was developed to show the feasibility of computer programs for providing minimum weight structure under certain structural loading conditions, and was later improved to include composite materials as well as metallic construction. Forward-swept wing structures such as the X-29 were investigated under a DARPA program. In the past decade, structures engineers at the Lab have led the field in the development of "aeroelastic tailoring," which is defined as "the embodiment of directional stiffness into an aircraft structural design to control aeroelastic deformation, static or dynamic, in such a fashion as to affect the aerodynamic and structural performance of that aircraft in a beneficial way." The FACES (Flutter of Aircraft Carrying External Stores) computer program was extended and applied to the A-10, F-15, X-29 and other aircraft. External stores flutter had always been recognized as a serious problem, due to the infinite variety of possible configurations. Some violent cases occurred in the 1950s during tests of the F-80 and F-94. But not until the advent of computers were engineers able to define the critical and non-critical cases and prioritize studies of the phenomenon.

The wing/store flutter suppression wind tunnel demonstrations were a major accomplishment of the early eighties. Tests conducted in the NASA sixteen-foot transonic dynamics tunnel validated many different control laws developed by researchers in the United States, Britain, France, West Germany, and Israel. In the first phase of the program fixed control laws were digitized, and in the later phases adaptive control concepts which adjusted for a wide range of store configurations were successfully demonstrated for wing/store flutter suppression. During 1986 an adaptive flutter suppression system (AFSS) was tested on a one-quarter-scale F-16 model. In some cases the AFSS was able to suppress flutter 30% above the unaugmented flutter speed -- an outstanding result. A broad technology base for flutter evaluation and prevention was established, leading to increased store carrying capabilities, mission effectiveness, an expanded flight envelope, and improved survivability. The installation of a flutter suppression system, if done early and integrated well, can extend aircraft performance without significantly increasing control system hardware.

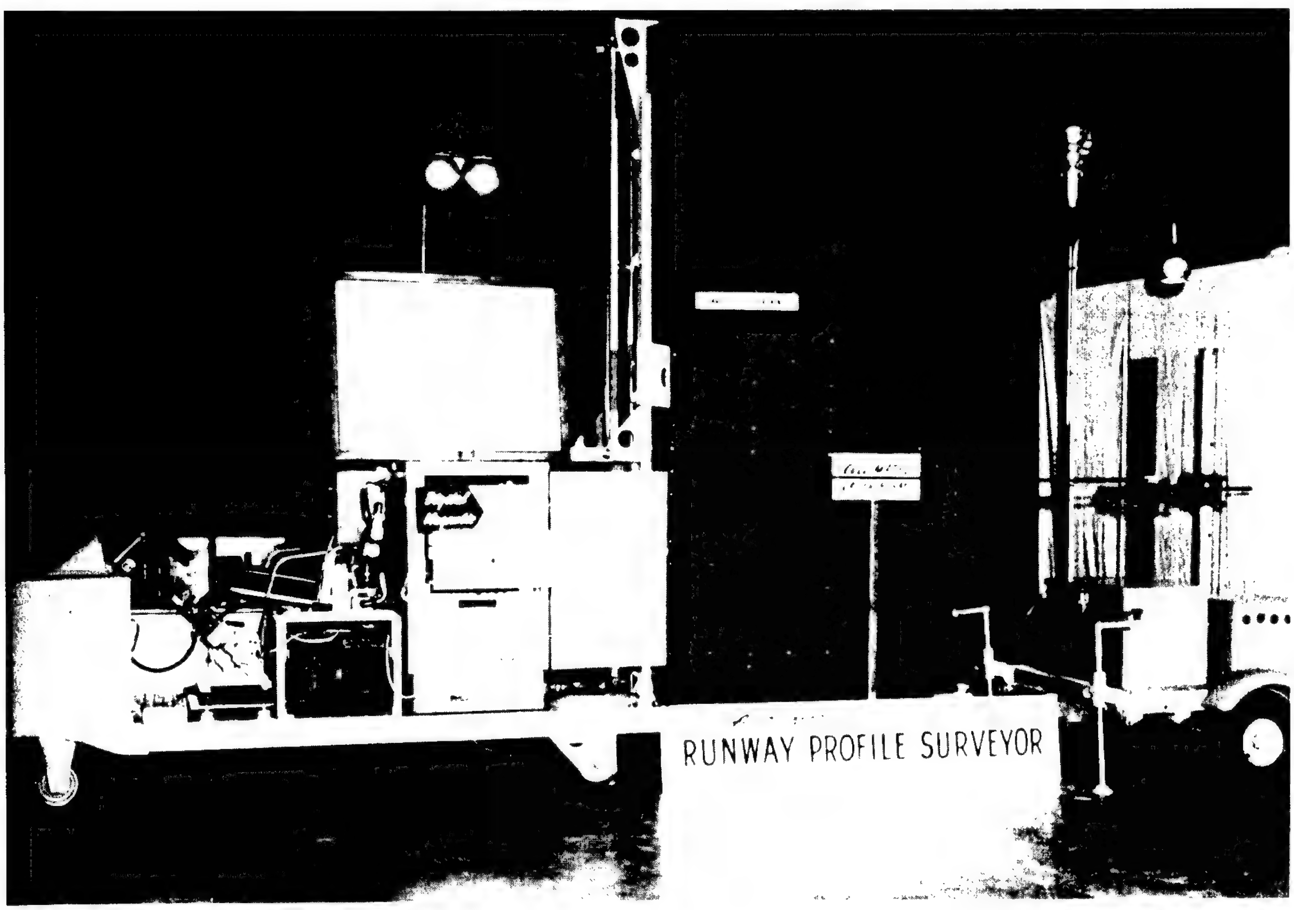
In 1983 the Branch moved on to an even more intractable problem. Existing flutter prediction methods using linear aerodynamics are not applicable to the difficult transonic regime, where equations governing flow are inherently nonlinear. The lower safety margin requires that weight penalties be minimized to prevent flutter.

Accordingly, Dr. James Olsen of FDL contracted with Boeing Seattle to develop a new method (called XTRAN-3) for predicting unsteady transonic flow over clean, swept wings. The first known transonic flutter prediction using an unsteady aerodynamic theory was achieved, and testing commenced at NASA Ames and NASA Langley to evaluate the program's applicability to different aircraft types. The XTRAN-3 program has been an outstanding success in predicting transonic flutter phenomena, and has recently been adapted under a joint AF/NASA program for use in state-of-the-art computers. It is now applied to the design of most new aircraft surfaces.

All in all, the study of flutter phenomena has been one of FDL's outstanding successes over the past five decades. New technologies have been shared with NACA, NASA, the Federal Aviation Administration, and the other armed services, and Lab engineers have acted as consultants to allied governments and corporations.

Dynamic Loads

The Lab and its predecessors have long conducted analytical and statistical studies of dynamic loads, that is, the stresses or loads to which an aircraft can be subjected without exceeding its limits. Sink speed, for example, is the velocity at which a landing aircraft touches the ground surface. Many variables are involved in determining optimum sink speed, and one of the first major studies of this phenomenon was



The Runway Profile Surveyor measures surface profiles of landing areas, runways and taxi areas to help predict the large and often overlooked dynamic loads produced during ground operation of aircraft.

conducted during the Berlin airlift. The criteria developed from this study were applied to most later cargo aircraft and bombers. The twin tail of the B-24 sometimes caused stabilizer failures during wartime flights, and tests conducted in 1945 aided in establishing dynamic loads criteria in this area. Engineers established the requirement that landing gear be designed for the loads associated with spin-up and spring-back. A study headed by Lee Wasserman in 1945 demonstrated that certain main gear failures in a B-17 were caused by spring-back loads. Wheel spin-up, the ability of landing gear wheels to match the speed of the aircraft to reduce dynamic landing loads, was studied in the late 1940s. The Lab produced a comprehensive monograph on the subject in 1963: ASD-TDR-62-555, "A Rational Method for Predicting Alighting Gear Dynamic Loads."

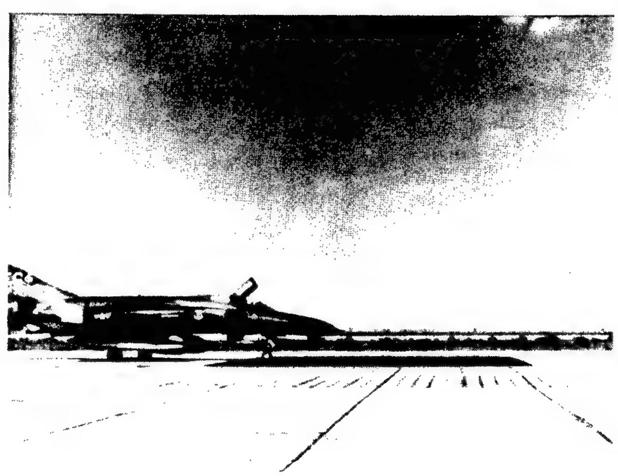
Loads resulting from uneven takeoff, taxi and landing surfaces were an even more intractable problem, since computers were not then available. Some studies of rough runways were conducted before 1950, and Lab experimentation with a C-141 resulted in "Methods for Analyzing Flight Vehicles during the Taxi Condition" in 1961. The Lab also developed the unique "Profilograph," an instrument which could rapidly measure runway surface profile irregularities as a function of distance and record them for analysis for criteria in the MIL 8800 series spec. During the late sixties the Dynamic Loads Group used the Profilograph with a T-37A to gather data on a variety of landing surfaces. Because of the special needs of aircraft in Southeast Asia at the time, this project was considered high priority. Operations from such airfields were quite common and there was a need to determine their influence on structural loads.

In the early seventies the Division provided computer analysis technology for determining the adequacy of the X-24 lifting body aircraft landing gear for sink speeds to ten feet per second, in performing landings. The landing gear were stock equipment chosen from available inventory. The dynamics group also explored

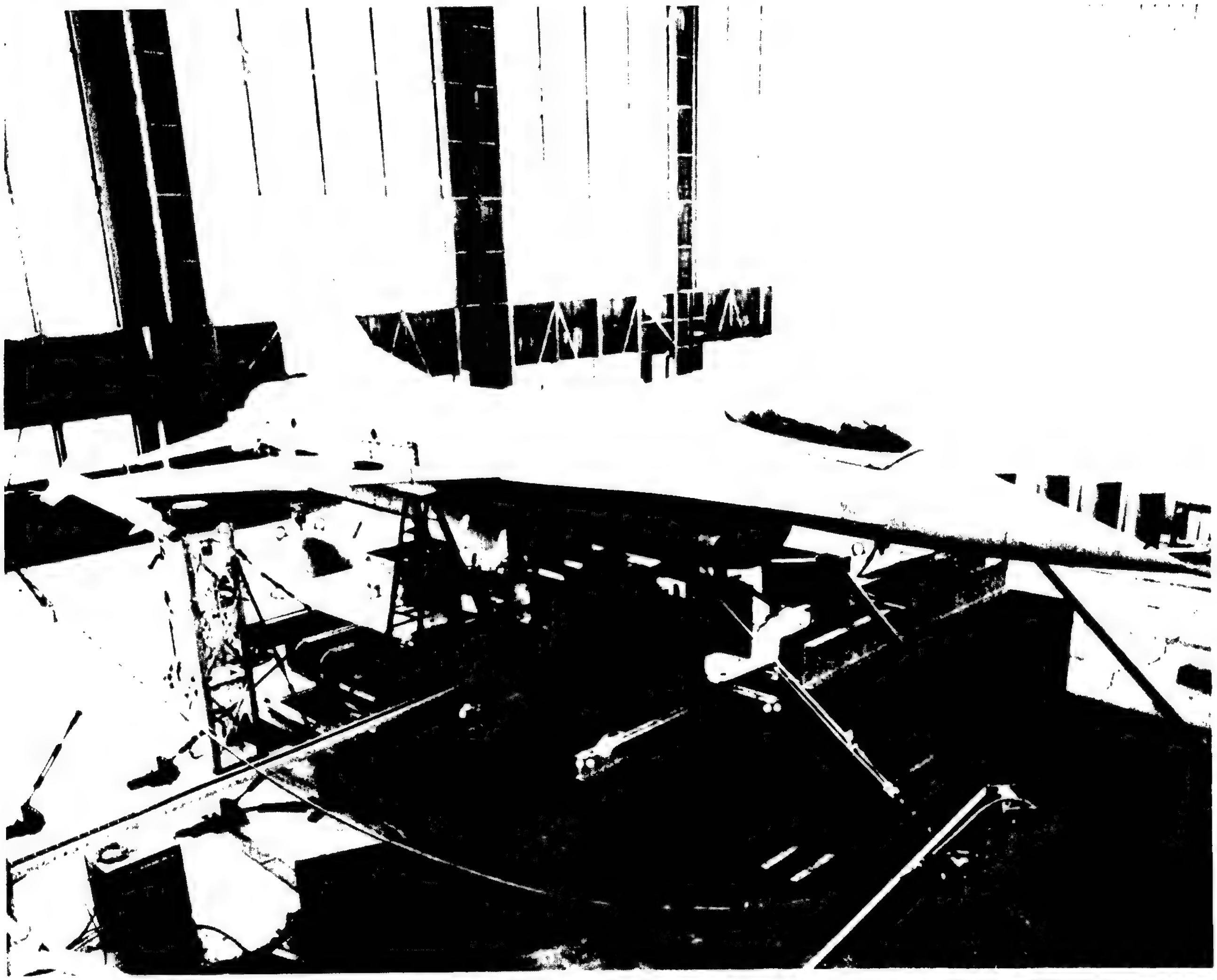
AM-2 repair mats developed in response to a need for rapid repair techniques for damaged runways. The war in Southeast Asia revealed many new needs like this one.

wheel and skid gear instabilities, buffet, store ejection, and a number of prediction and analysis techniques for soft field and battle damaged airfields. In 1978 the group completed a major project, "Structural Response of Fighter Aircraft to Damaged and Repaired Runways." Rapid runway repair techniques had been perfected as far back as World War II, but the dynamic loads response of aircraft to such runways was still difficult to evaluate.

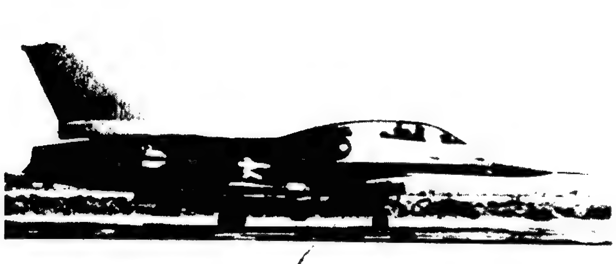
The FDL developed a computer program, TAXI, to predict the dynamic response of a variety of combat-loaded aircraft, using an F-4 as



Test of an AM-2 repair mat with an F-4. The aircraft has an additional high-pressure strut, developed by the Loads and Criteria Group.



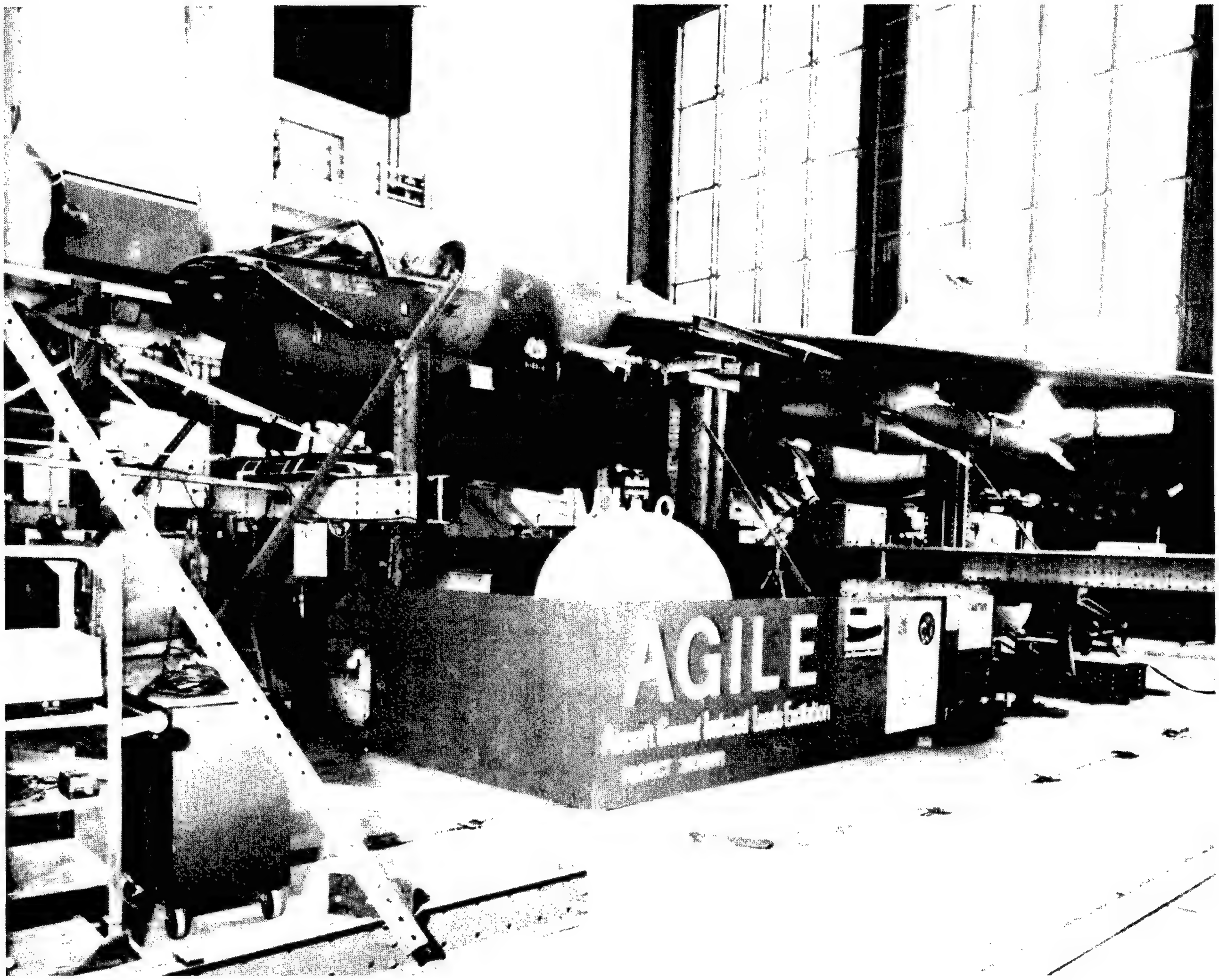
The Aircraft Ground Induced Loads Excitation Facility (AGILE) saves much of the cost of field testing. Here a YF-16 undergoes tests.



Fully loaded F-16 traversing an AM-2 repair mat during a loads measurement test.

a test bed. TAXI demonstrated that the F-4's landing gear was designed for high sink speed landings, but not for taxiing over rough surfaces; the incompatible designs left the aircraft vulnerable to rough runways. The Lab delineated ways of improving the landing gear, and feasibility of the new design was borne out by exhaustive tests at Edwards AFB in November 1978.

Runway test measurements in the A-10, F-15, F-16, and F-111 validated and expanded the TAXI computer program, and during the early eighties, interim surface roughness criteria were developed for a variety of aircraft. As this work progressed, it significantly enhanced the sortie



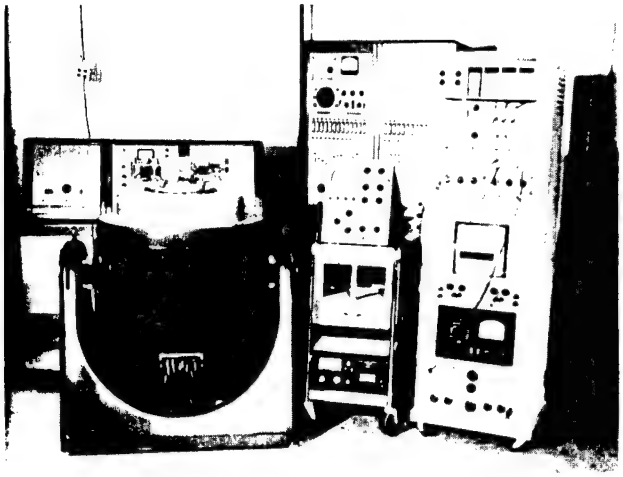
AGILE tests of this A-7 aircraft provided engineers with valuable data.

generation capability of fighter aircraft in response to airbase attacks. Since field testing of aircraft response to damaged runways is expensive and time consuming, in 1984 the Lab commenced construction of the AGILE (Aircraft Ground Induced Loads Excitation) facility in an effort to minimize aircraft tests and improve TAXI validation techniques.

Three independent hydraulic shakers (adapted from the automobile industry) are capable of simulating the vertical input to tires and landing gear during runway operations. Sensors are attached to the test aircraft. Initial experimentation was conducted on a YF-16, with encouraging results. The average cost of such a test in 1984 was about $50,000, while runway field testing ranged between one and two million dollars per test. The AGILE simulator is expected to save the taxpayer millions of dollars in field test costs.

Vibration

Long-term aircraft vibration was first identified in reciprocating engines and propellers. The firing sequence of reciprocating engines along with the passage of the propeller near the structure caused excessive vibration which led to fatigue failures in the engine mountings and other nearby structures. Aircraft Lab studies of this phenomenon, pioneered by



Vibration analysis on structural components was conducted in 1960s using shakers like this one. Some of these shakers are still in use.

In the mid 1960s a KC-135 was used to fly the Zero Gravity Passageway Study Rig, providing brief periods of weightlessness for testing space structure vibration.

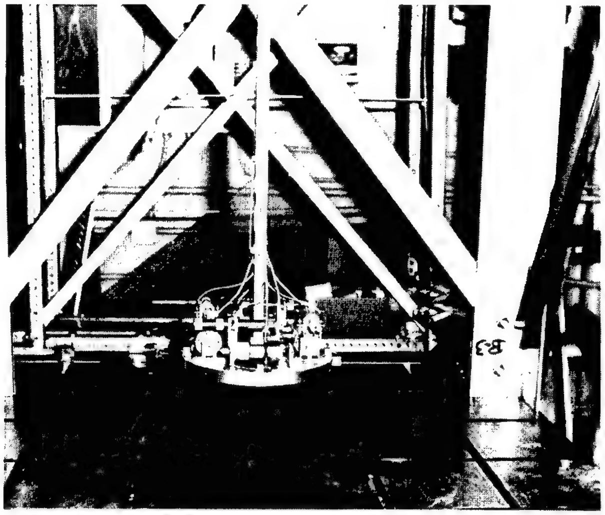
Howard Magrath's team in 1942, were used by the old Dynamics Division as a basis for its work with more advanced aircraft.

Jet aircraft sometimes experience vibrations of sufficient intensity to cause major failures, and the problem is even more critical for spacecraft. The Airplane Lab had solved the problem for propeller aircraft with the reciprocating engine/propeller combination, and serious work began on jet engine vibration in 1951. At first, the lab concentrated on improving existing vibration damping devices, but the random nature of jet vibration made this approach unfeasible. In addition, entirely new types of vibration manifested themselves in high-speed jet aircraft, the result of separated flow, base pressure fluctuations, and the like.

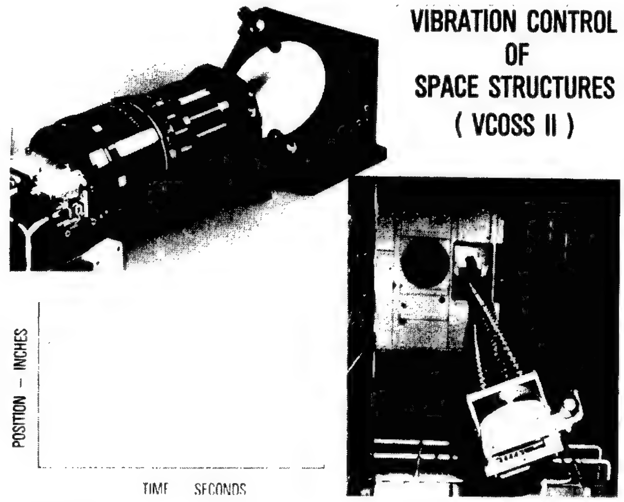
The early versions of the Snark missile suffered a high failure rate due to vibrations of vacuum tubes then used in guidance and control systems. The Lab solved this problem by upgrading the decibel level which the missile body and equipment could tolerate, using sound blankets and thicker body skin. In the H-21 helicopter, the fuselage and pylon support structures were strengthened to solve a similar problem with frequencies generated by the rotor blades. Early helicopters were susceptible to mechanical instabilities which often led to the loss of the vehicle. It was clear by the mid-forties that a multifaceted approach to the vibration problem was called for, and the Lab launched statistical and theoretical studies during the 1950s. As a result, design parameters were improved across a wide spectrum of aircraft types. A large number of vibration sources, ranging from the jet powerplant itself to random aerodynamic vibrations, were identified. By 1954 new techniques were being applied to jet aircraft design; between 1955 and 1958 significant advances were made in helicopter design. In the long run, vibration prediction techniques perfected at the Lab have been essential to all later airframe designs.

The first practical engine vibration isolation device was developed at the Airplane Lab by Wilbur Stotz. This device, when manufactured under license by industry, became world-famous as the Lord Engine Mount.

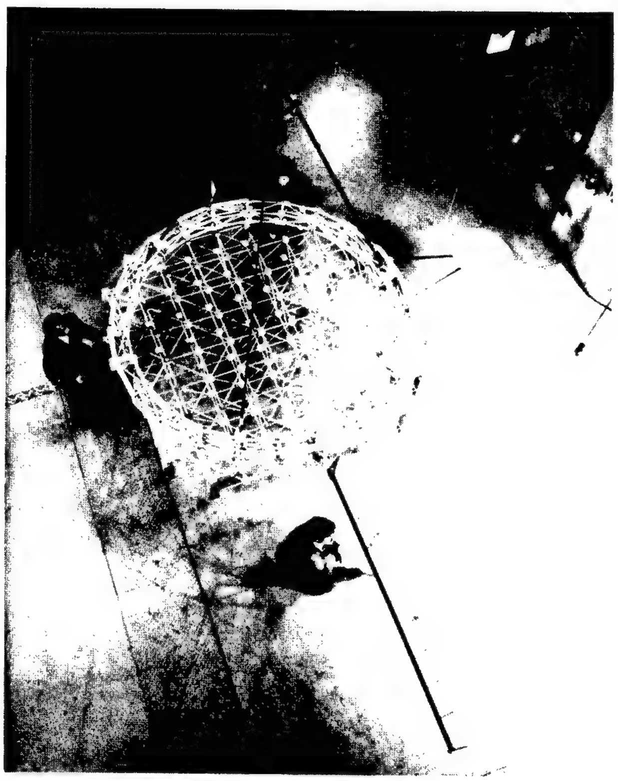
Rapid changes in fighter aircraft design in the early seventies revealed a new range of vibration problems. A new set of prediction techniques was developed by 1974, using data from an RF-4C test vehicle. The technique is based on



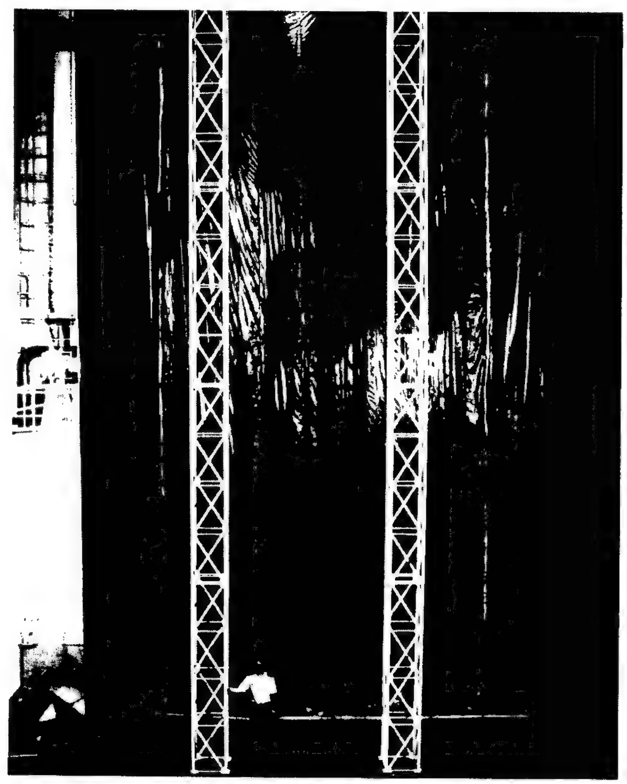
The Advanced Beam Experiment will study the active control of vibration in a bending torsion beam. Results will be applied to advanced space structures.



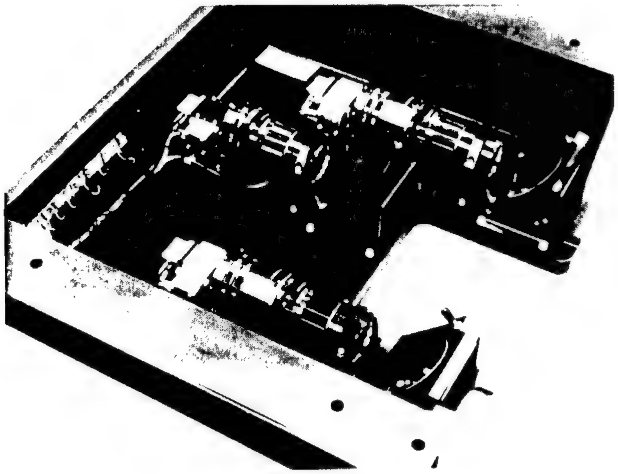
VCOSS II technologies developed at FDL provide valuable data on active vibration control in large space structures.



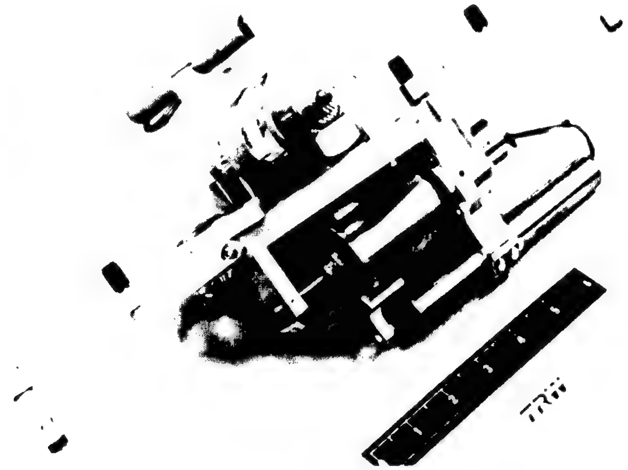
Large space structures are subject to vibration from onboard equipment or space debris impact. Note the frailty of this model.



These 12 meter trusses will be used in experiments on ground suspension and active vibration control in space structures.



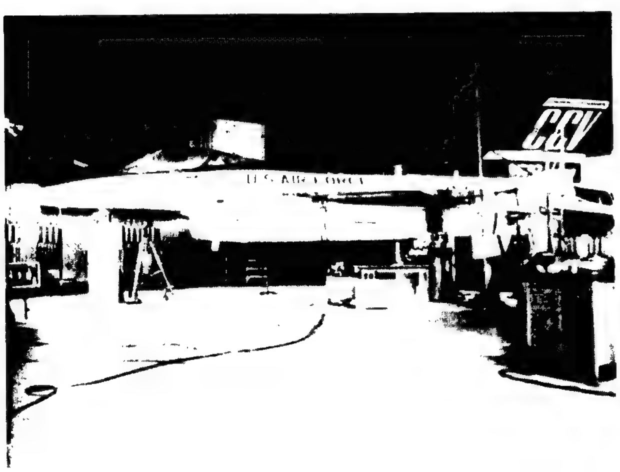
Three optical position sensors developed for the VCOSS II program. The sensors convert linear or angular displacements of laser sources into electrical signals for controlling vibrations.



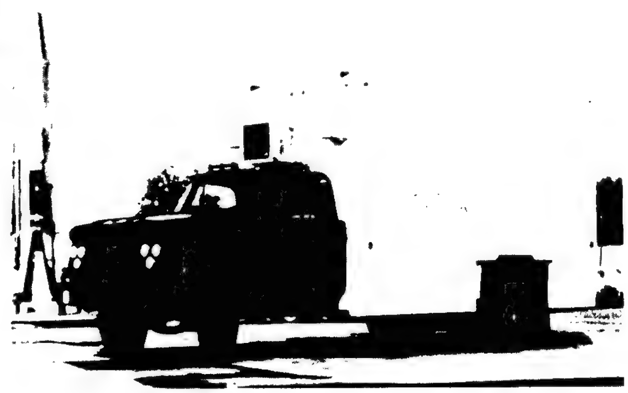
A VCOSS II actuator station, using a magnet and coil assembly to produce inertial forces for controlling vibration in a large space structure.

the assumption that excitation and response data from existing aircraft can be extrapolated to estimate the vibrations of a new vehicle. After the creation of the Structural Mechanics Division this work was continued by the Field Test and Evaluation Branch, Vibration Group. New methods were developed for determining linear and angular structural responses to mechanical, acoustic and unsteady aerodynamic vibratory excitations. Design criteria were also established for vibration problems in advanced components such as laser systems and space structures.

A conference on Aerospace Polymeric Viscoelastic Damping Technology, held in Dayton in 1978, led to new vibrations studies at FDL. In conjunction with the University of Dayton, the Structural Mechanics Division offered several short courses on vibration damping technology to disseminate information on viscoelastic materials to government and



GF-16 GVT aircraft undergoing vibration tests in the chamber of the Large Sonic Test Facility.



One of the Data Acquisition and Analysis vans used by the Structural Vibration Branch to provide mobile capability for multi-channel recording and editing.

Passive and active control of space structures: 12-meter truss comparison.

industry. Work also continued on high cycle fatigue damage to fuselage structures, and damping for high energy lasers and space structures such as satellites.

In 1981 the Vibration Group became the Structural Vibration Branch, with a field test group, a data analysis group and a dynamics engineering technology group.

Passive and Active Control of Space Structures (PACOSS):

In 1984 the Structures ADP Branch demonstrated that passive damping could be incorporated to minimize vibrations in large space structures. Such structures must be precise in pointing and tracking in the presence of disturbances. Ground tests were performed on a sixty-foot tall structural truss with damping nodules on the diagonals containing viscoelastic material. Vibrations were induced and measured through sensors attached to the truss. PACOSS will aid in the success of space structures such as antennas, optical surveillance satellites, and lasers.

Strategies for the Future

For the past quarter century most "ordinary" structures testing has been conducted by industry, while the Division has concentrated on more advanced work. Testing of current aircraft will continue on a small scale (the F-15, for example, is now undergoing tests at Building 65) in order to train engineers and to keep up with and critique methodologies used by contractors. During the coming decade, however, structures and dynamics technology will move forward in a number of fields. Project FORECAST II points toward explorations of innovative structure technologies in a variety of weapons systems, from subsonic aircraft to satellites. The Laboratory Strategic Plan calls for in-house research and development on high-temperature fatigue and fracture, structural analysis and automated design; vibration testing of space structures, aeroelastic tailoring, and aeroservoelasticity, among other technologies. Other Division plans include research in survivable structures, advanced aeronautical structural concepts, aircraft structural integrity, spacecraft structures, and the expansion of the structures and dynamics technology base. Ongoing projects include structural improvement of the existing fleet of operational aircraft. As planning for the National Aerospace Plane goes forward, the Division expects to contribute to hypervelocity vehicle technology. New challenges which did not exist for 1960s hypersonic research will have to be met: for example, testing hydrogen-fueled vehicles and actively-cooled structures. The Flight Dynamics Lab was the first organization in the country to begin work in these areas, and we can confidently predict that it will continue to lead the field.

Advanced Development at the Flight Dynamics Lab

Over the years the Flight Dynamics Laboratory has engaged in a number of projects that were too large or complex to be subsumed under one division or branch. These Advanced Development Programs, as they are now called, have usually been established under separate offices reporting directly to the front office. Engineers and facilities from all divisions may contribute to an ADP -- and are usually anxious to do so, since an ADP represents the actual construction of a new flight vehicle rather than just an output of technical reports. The "advanced development" concept dates from the Vietnam era, when new weapons systems had to be developed more quickly and efficiently than in the past. The ADP structure owes a great deal to the former Lab commander Col. Charles Scolatti, who pioneered the technology

During the mid to late 1960s the V/STOL Technology Division contributed to the development of the XC-142A tri-service experimental V/STOL transport.

integration concept. While ADPs often produce remarkable achievements, they are not without their problems. The creation of a new ADP usually brings a large infusion of new R&D funding, along with the attendant managerial and financial structures to administer the money; but the actual research and development must be done by the Lab's existing manpower pool. Limited resources means a very careful allocation of manpower and facilities, and at the same time engineers and scientists must take on management duties. ADP managers must spend more time on managing and less time on research, and must shoulder increased responsibility and visibility at higher command levels. It should be emphasized that the creation of an ADPO (Advanced Development Program Office) is primarily a financial arrangement; the actual research and technology are not separate from that of the division or branch where it originates.

This chapter presents highlights of advanced development technology during the past three decades. In addition to programs within the Flight Dynamics Lab, support is also offered to projects in AFWAL or other military labs. FDL contributed significantly, for example, to the development of the C-141 transport, the XB-70, the X-142A V/STOL transport and the C-5A.

V/STOL Technology Division

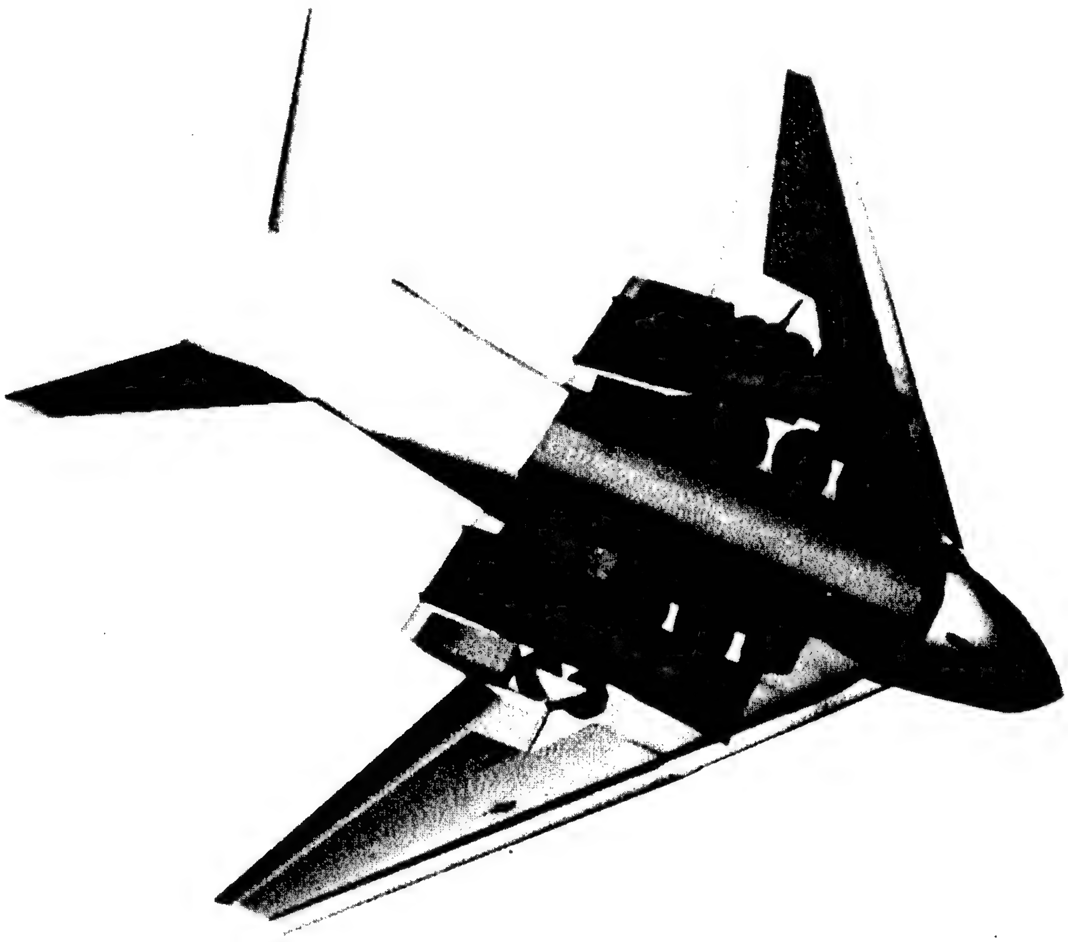
In September 1965 a sixth division was established within FDL: the V/STOL Technology Division, whose purpose was to pull together the previously unorganized research on vertical and short take-off and landing concepts. Since V/STOL work was already under way in various military labs, including the Vehicle Dynamics Division, this division's functions were mostly managerial. It was the focal point for collection and dissemination of V/STOL data and acted as liaison with the other armed services and with foreign governments. It reviewed all ongoing research to identify gaps and prevent duplication of efforts. As the scope of its research broadened, the V/STOL Technology Division was transformed into the Prototype Division.

Prototype Division

The Prototype Division of FDL was formed in 1971 to formulate, plan and manage exploratory and advanced research in aerospace research vehicle prototypes. William Lamar, then Deputy Director, conceived of this division as a means of integrating the complementary work being conducted by the various separate divisions. The first major project was to have been the YF-16, but this program was transferred to ASD as the Lightweight Fighter Project Office. V/STOL, Remotely Piloted Vehicles, and non-nuclear survivability/vulnerability were the Division's other early priorities. Both in-house and contract research was conducted. In the early seventies the Division developed the XQM-103 RPV, the ATCASA Integration Vehicle, the Composite Maneuver Augmentation (COMMA) concept, and the CAS (control augmentation system) STOL Fighter vectored thrust/direct side force control.

Since most of the prototype projects under way in the late seventies were aeromechanics-related, the Division was transferred into Aeromechanics as the Vehicle Synthesis Branch. After only about five years, however, this solution proved inadequate: the evolving concept of technology integration required ADP support from all

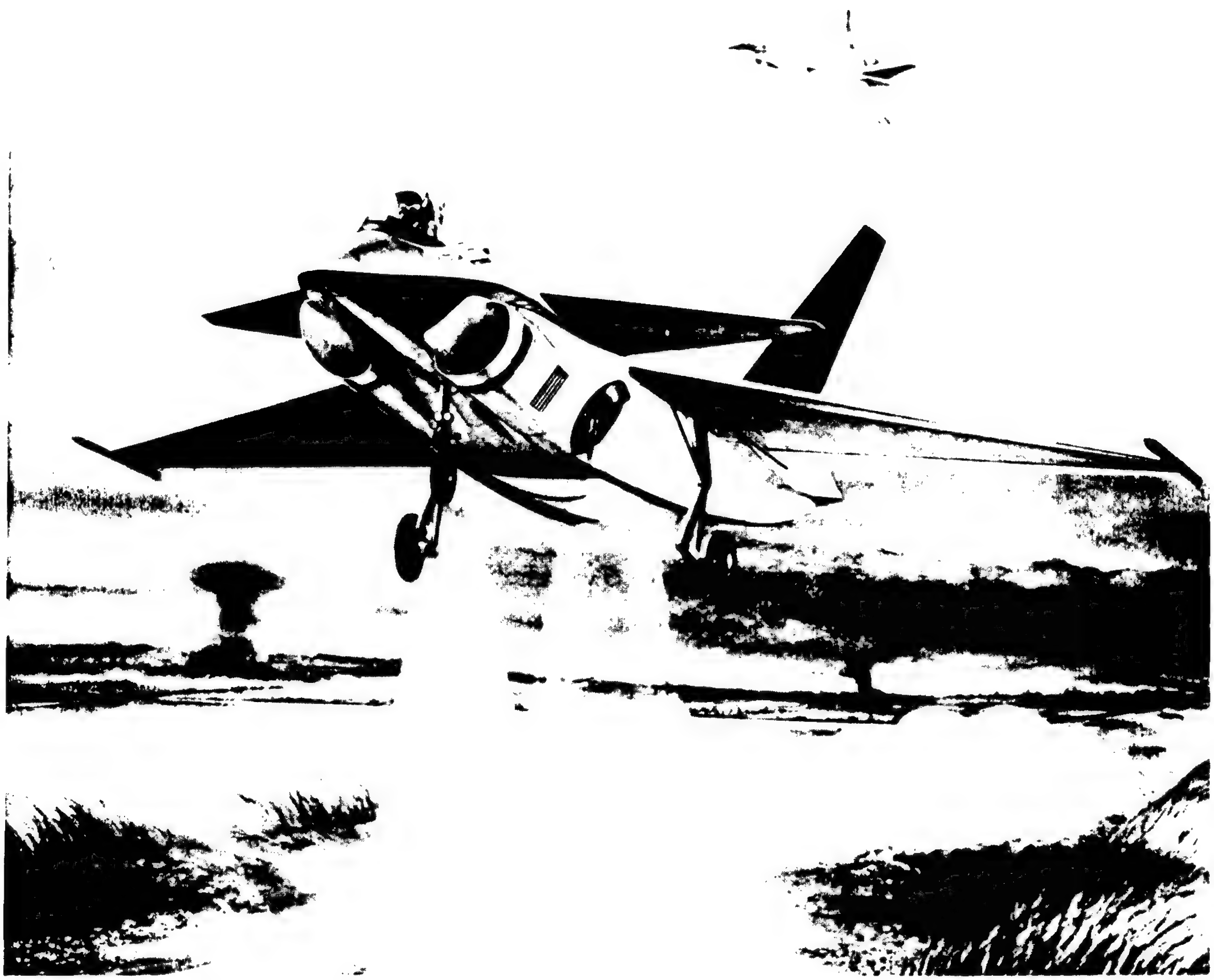
Remotely piloted vehicles like this one were the responsibility of the Prototype Division in the early 1970s.



Today's prototypes are designed in the Technology Assessment Division. This aircraft was designed using the Integrated Design and Analysis System (IDAS), an interactive computer program that allows the designer to check out complex geometries quickly and efficiently.

divisions. Accordingly, the Technology Assessment Division was created.

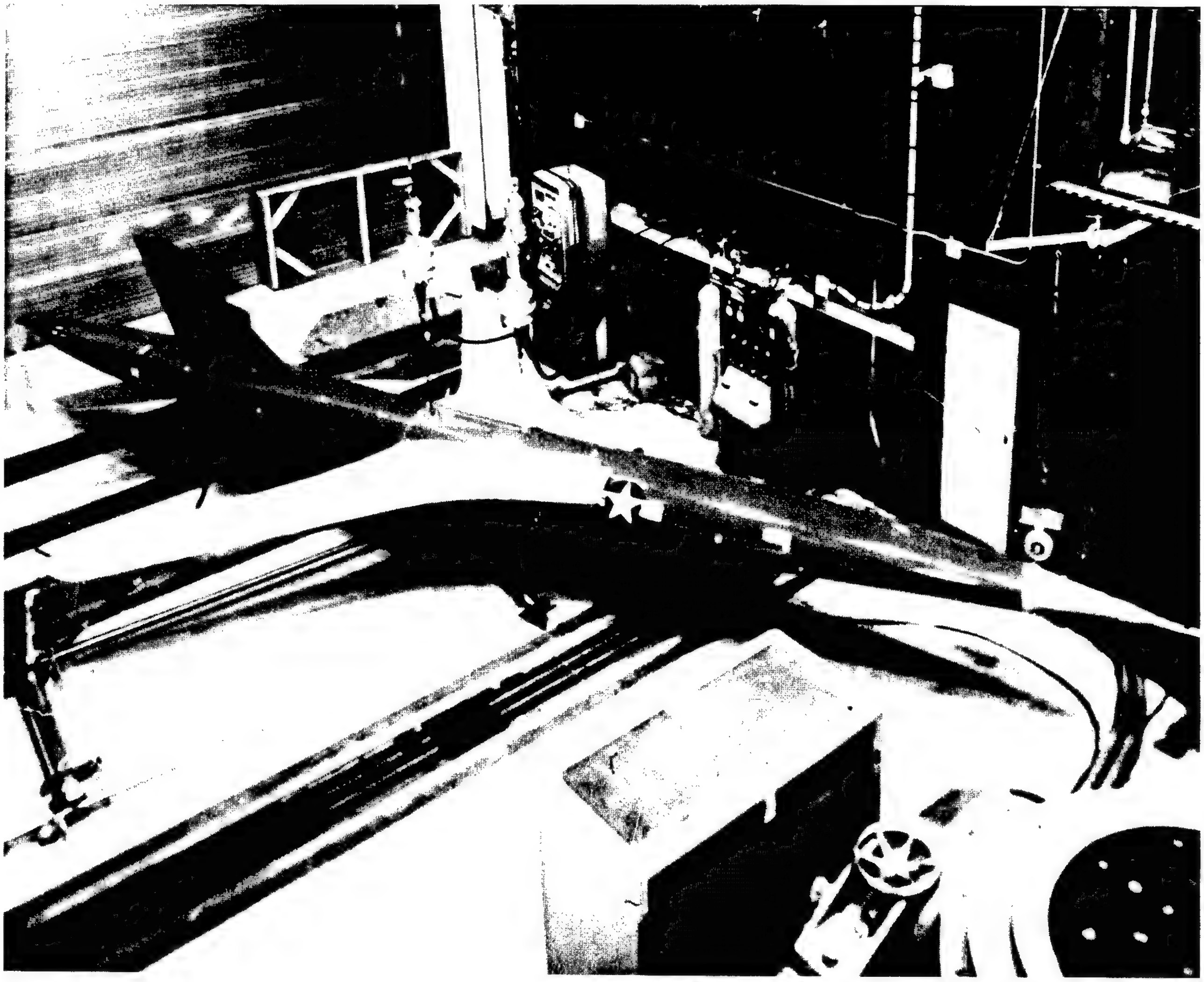
Today the Technology Assessment Division is responsible for evaluating new concepts on the cutting edge of aerospace technology. The decisions made in this office can have a profound effect on all other divisions, as it points the way to new projects and programs. The Division includes analysis, concepts, and design branches. The mission includes the definition of advanced concepts, assessing their military effectiveness, and identifying critical technologies for future aerospace applications. Prediction of vehicle characteristics and mission analysis is a big part of the Division's work, and of course considerable attention is given to cost effectiveness analysis. Perhaps the most important recent contribution of the Technology Assessment Division is the Computer-Aided Design (CAD) program, which has proved invaluable across a wide spectrum of aircraft designs and is now being used to develop the National Aerospace Plane. It began in the early eighties as IDAS (the Interactive Design and Analysis System), under contract with Rockwell International. IDAS was the first comprehensive effort to integrate existing programs into a single unit to provide a conceptual design tool using statistical analysis techniques to initiate aircraft design studies.



The Technology Assessment Division is now studying a Short Take-Off/Vertical Landing (STOVL) fighter.

Supercritical Airfoils: An Example of Advanced Development

By the mid 1950s aircraft capable of breaking the sound barrier had become common, and engineers soon recognized that future combat aircraft would have to operate extensively in the transonic range. The search was on for the optimum wing configuration for such airplanes. In the 1960s scientists at NASA Langley developed the supercritical airfoil, and early flight demonstrations were successful. The Air Force decided to join the research effort and assigned the task to the Prototype Division, which adopted an F-111 aircraft as a test bed. In 1970 the TACT (Transonic Aircraft Technology) program was approved to follow up the preliminary findings. General Dynamics was the contractor, and the effort included support from NASA Ames, Langley and Dryden and the Flight Test Center at Edwards AFB. The new wing included a high lift system and had a three-section leading edge Krueger flap and a four-section, single slotted Fowler trailing edge flap. FDL's Structures Test Facility conducted stress loads testing. Flight tests revealed a 12% increase in drag divergence Mach number, and a 24% reduction in drag or a 20% increase in lift. Buffet characteristics were improved and the normal force coefficient at buffet intensity rise

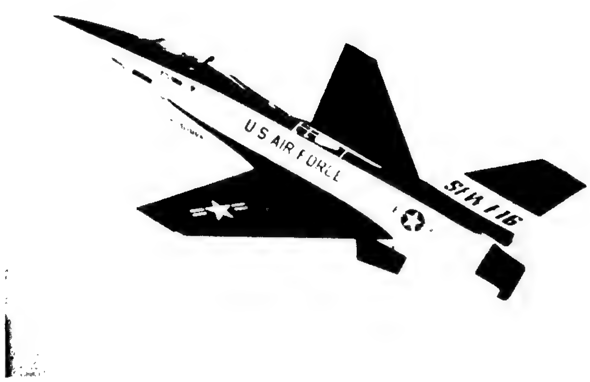


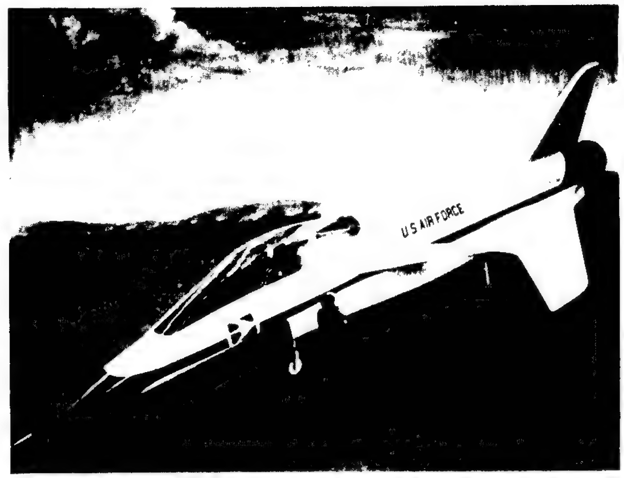
This remotely piloted vehicle was given a new supercritical wing to study transonic aerodynamic concepts.

increased from 0.22 to 0.78. Externally mounted wing stores did not significantly affect performance. TACT opened up new areas of study in transonic aerodynamic technology, and subsequent aircraft designs have benefitted.

X-29 Experimental Aircraft

In the late seventies the Aerodynamics and Airframe Branch of the Aeromechanics Division began evaluation of forward-swept wing configurations. Studies by General Dynamics and by Lt. Col Norris Krone in his doctoral thesis had predicted that this design could produce weight reductions and enhance maneuverability. Krone, working with Grumman Aerospace Corporation, made a presentation to FDL in 1976, and a year later contracts were let for a feasibility study. A number of computer-generated designs were analyzed, and the decision was made to build an advanced technology demonstrator utilizing the forward-swept wing and aeroelastic tailoring technology. The joint program (with the Defense Advanced Research Projects Agency and NASA) was given the name X-29, and responsibility for development was granted to an ADPO within the Flight Dynamics Lab. Grumman Aerospace was given a contract to produce two aircraft integrating a number of advanced technologies, including the composite forward-swept wing



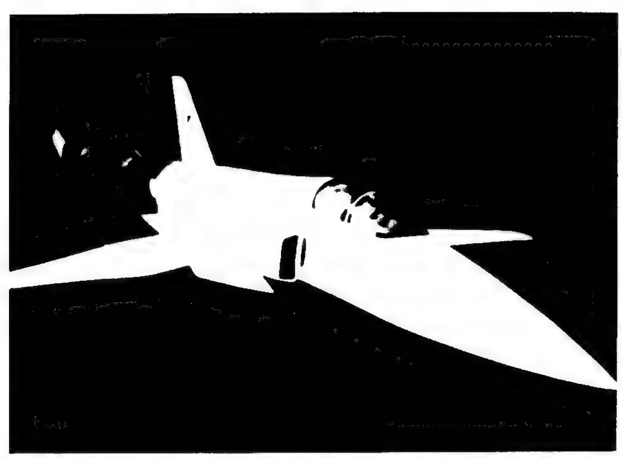


General Dynamics (left) and Rockwell International (right) submitted designs for the Forward Swept Wing competition, but Grumman Aircraft won the contract to build two X-29 demonstrator aircraft.

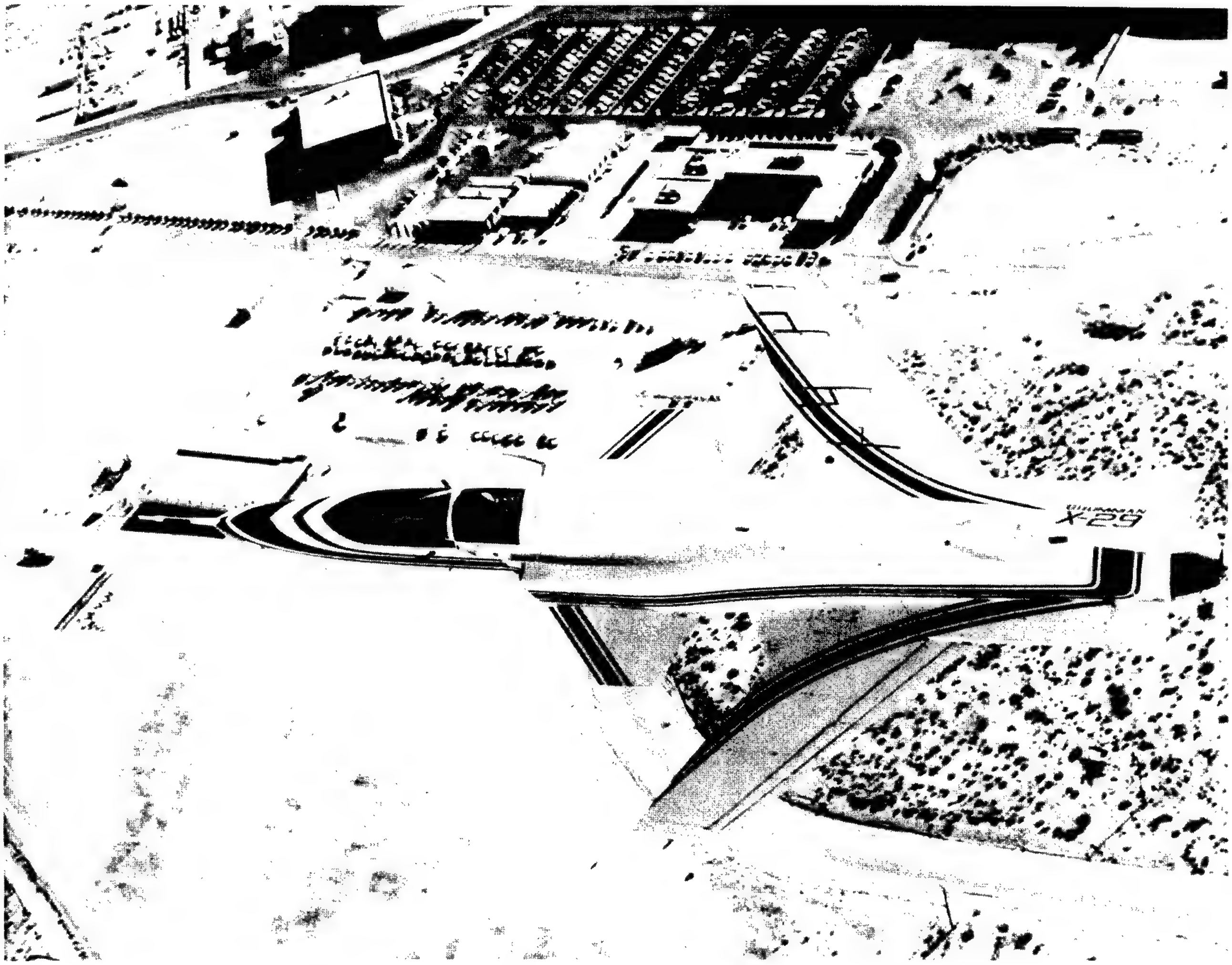
with discrete variable camber; close-coupled canards; highly relaxed static stability; and a triplex digital flight control system. The NASA Dryden Flight Research Facility, the Patuxent River Naval Air Station and the Flight Control Division co-operated in simulation testing of the software, and an engine-out simulation was conducted at the Air Force Test Pilot School, using a T-38. Wind tunnel testing was performed at NASA Ames, and half-scale freedom flutter tests at Langley. In-flight simulations were performed with the Lab's TIFS aircraft. The first two X-29 demonstrators were completed in 1983 and subjected to extensive ground testing. After a rollout ceremony attended by Vice President George Bush, the #1 aircraft was shipped to NASA Ames Dryden Flight Research Facility for further ground and taxi testing. The first test flight took place shortly thereafter. Throughout the history of the ADPO a "Future Applications Committee," with members from government and industry, was involved in data acquisition and exchange. For three years the Flight Control Division supported this ADPO with a variety of contributions, from a review of the first flight's safety to aerodynamic uncertainty and high angle-of-attack studies.

The X-29 has a take-off gross weight of 17,900 pounds, including four thousand pounds of fuel, and uses an F404-GE-400 turbofan engine. The forebody and cockpit are adapted from the F-5A, while the wings and aft fuselage are new designs. The main landing gear, control system actuators, and the emergency power unit system are F-16 components. The X-29 is heavily instrumented so that real time flight test data are available for evaluation. In addition, the X-29-2 aircraft is being modified for a spin chute system, support systems, and instrumentation specifically tailored for high angle-of-attack (AOA) flight testing.

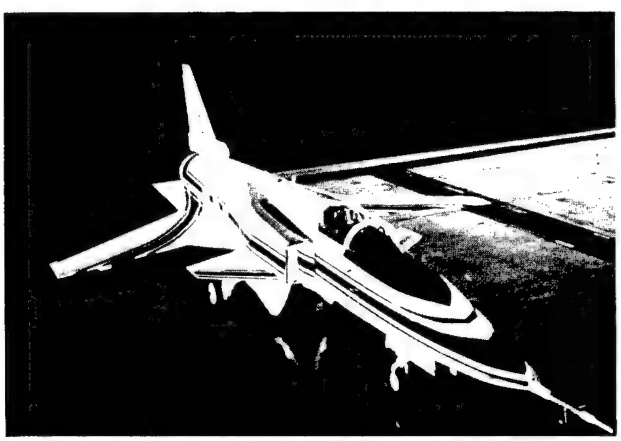
The program is a multiple phase flight testing task program using both X-29 aircraft. Initial



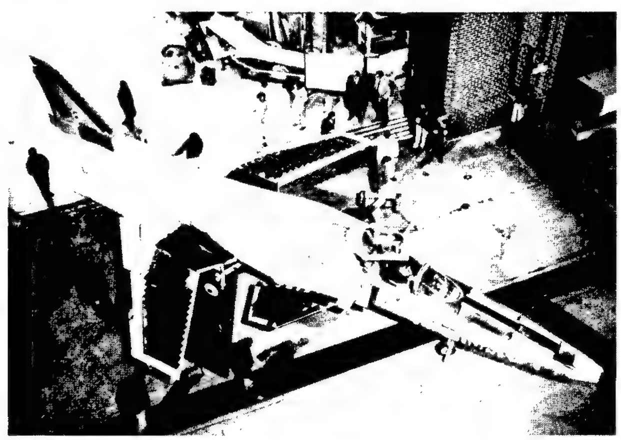
Extensive wind tunnel testing was conducted on the forward swept wing designs. This is a model of the Grumman design.



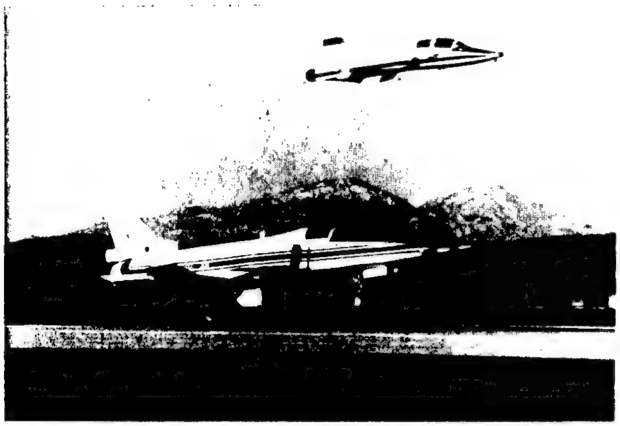
The X-29 flies over Edwards AFB, California, where its flight tests are conducted.



The dawn of a new age in technology integration. The X-29 integrates many advanced concepts in a single aircraft, most notably the forward swept wings.

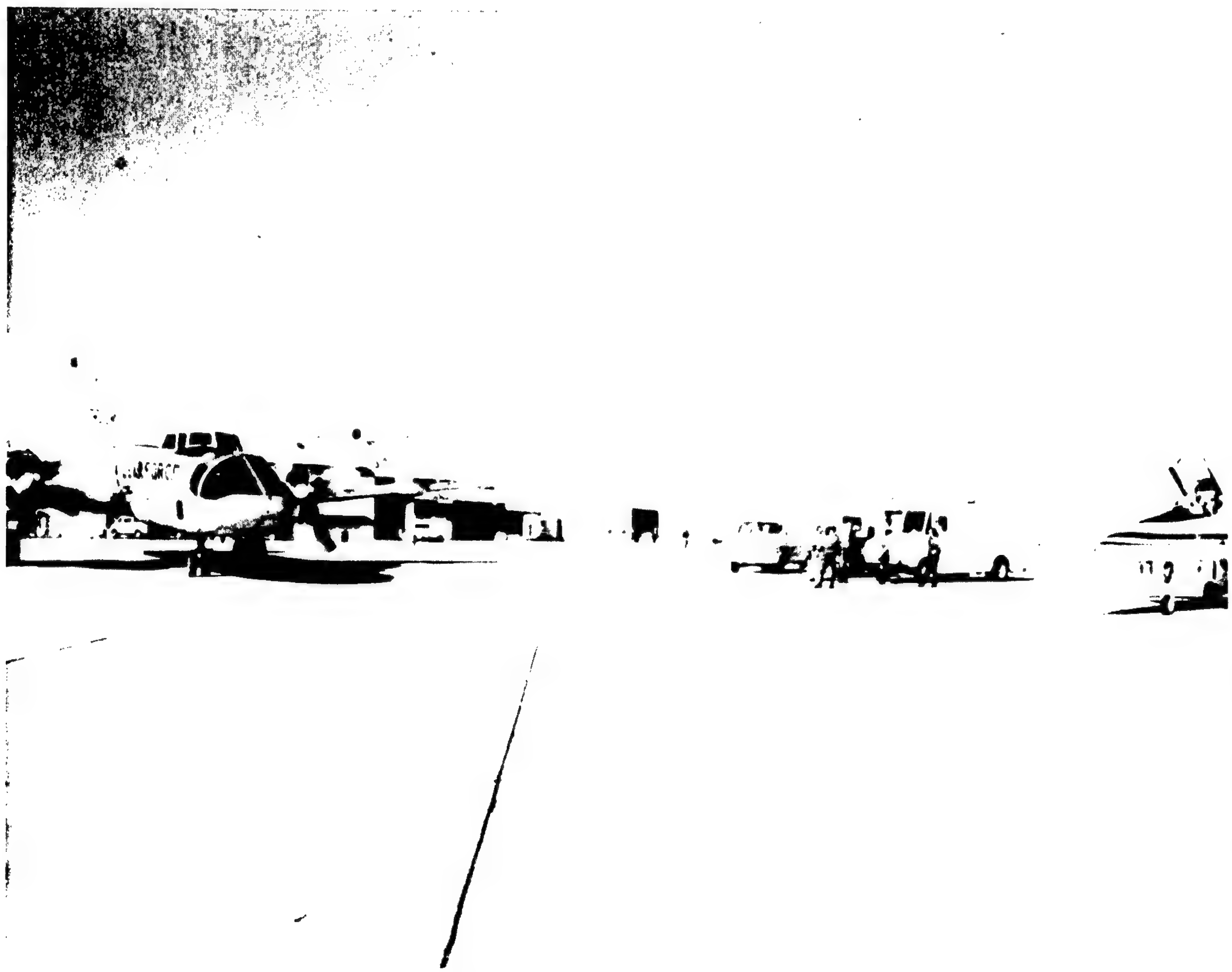


The X-29 wings are aeroelastically tailored composites. Without this technology, the forward swept wings would literally rip off at high speeds.



The X-29 has set a new record for the "X" series with over 200 successful test flights. The previous record was held by the X-15.

testing included flight demonstration and envelope expansion using the X-29-1. The follow-on phase uses the same aircraft primarily to obtain research data and quantify performance, divergence and loads, validate design analysis methods, and provide evaluations of handling qualities, military utility and agility metrics below 20 degrees AOA. The X-29-2, modified for AOA flight test above 20 degrees AOA, will evaluate predicted combat maneuvering potential at angles of attack up to 40 degrees and pitch axis maneuvering up to AOA limits, approximately 70 degrees.



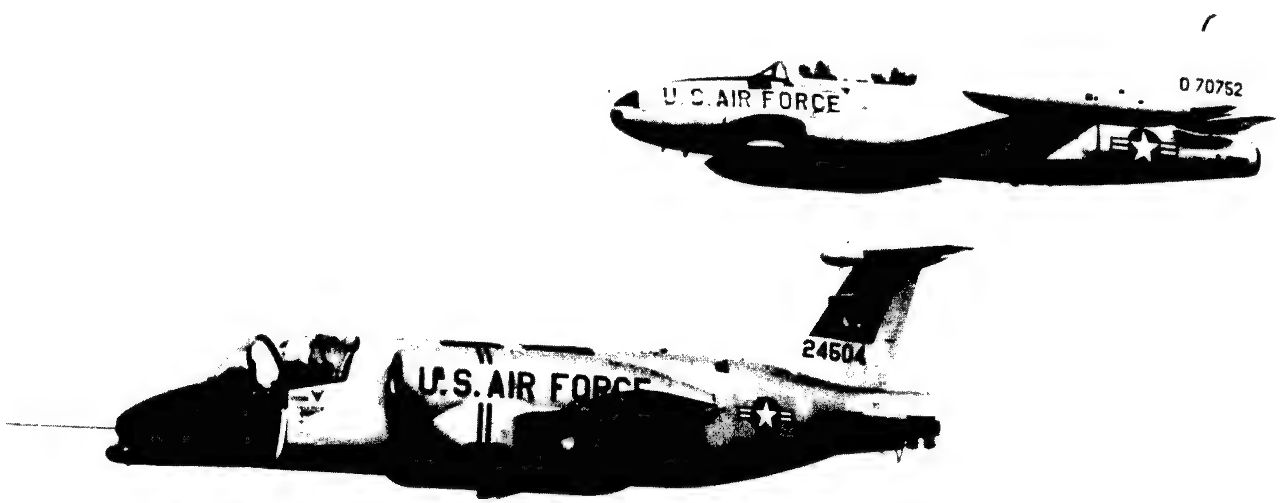
The X-29 flight control system was first tested in ground based simulators and then in the TIFS (left) before the X-29 ever flew.

Hummingbird XV-4B VTOL Research Aircraft Program

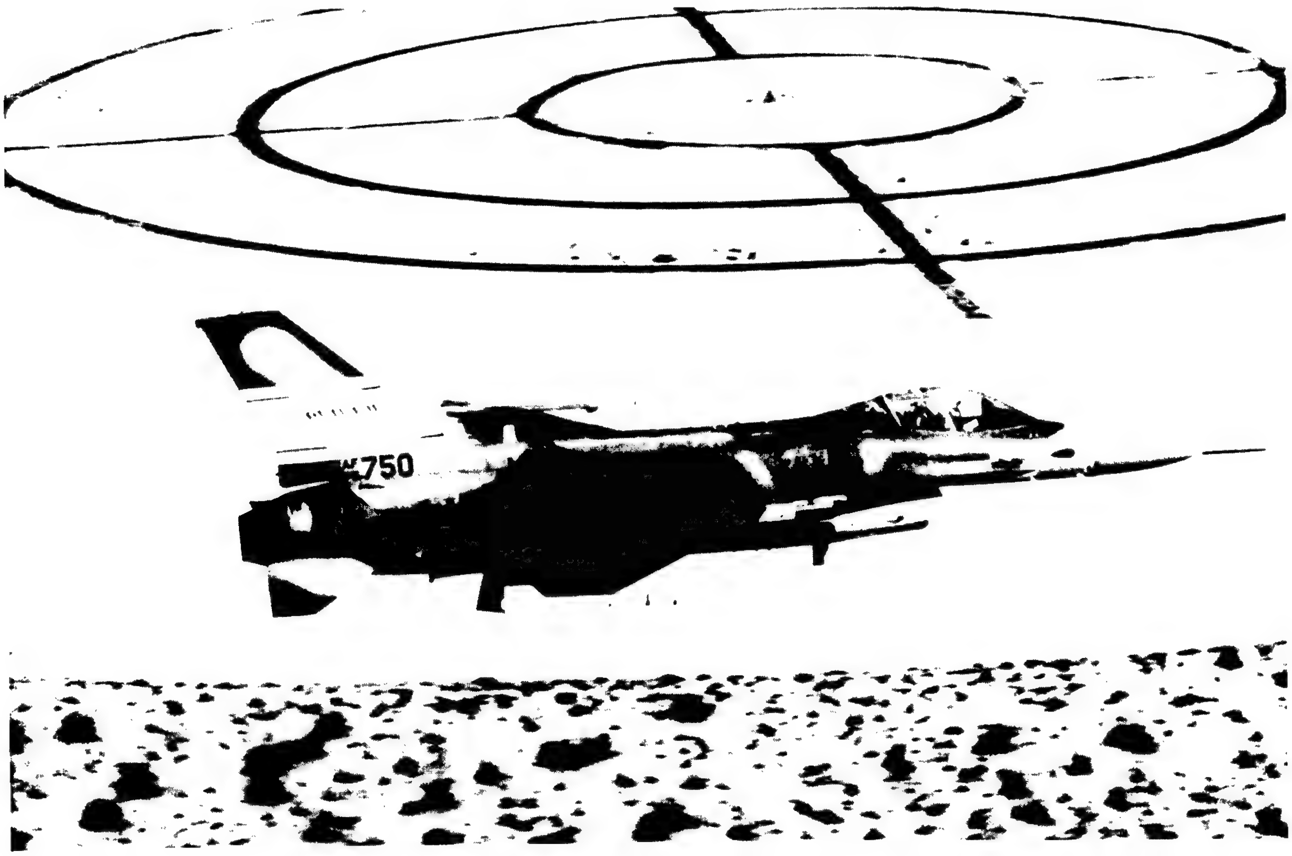
The Hummingbird VTOL project was one of the earlier V/STOL Technology Division efforts to develop vertical take-off and landing technology, and it looked promising until the test aircraft was lost during a flight from Dobbins Air Force Base. The program commenced in September 1966 when Lockheed-Georgia began extensive modification of an XV-4A, and at the same time wind tunnel and other tests were conducted. One of the more interesting innovations in this program was an inverted telescope and balance system, installed in the test vehicle to check VTOL operations in the safety of a captive flight device. The inverted telescope permitted raising the aircraft to ground plane heights up to fifteen feet, with freedom to change attitude while the engines were in operation. Ninety-five flight tests were planned; twenty-three had been completed when the aircraft was lost. Testing up to that point indicated that all design criteria would have been met. Though it ended in misfortune, the Hummingbird program contributed a great deal of essential knowledge for future VTOL research.

AFTI/F-16 ADPO

One of the greatest accomplishments of the Flight Dynamics Lab during the past two decades has been the development of the AFTI/F-16 flight demonstrator. In the past, new technologies developed by various laboratories or divisions were usually flight tested one at a time (systems development) but the flood of new ideas emerging from FDL and other organizations in the 1970s made this approach impractical. The Advanced Fighter Technology Integration



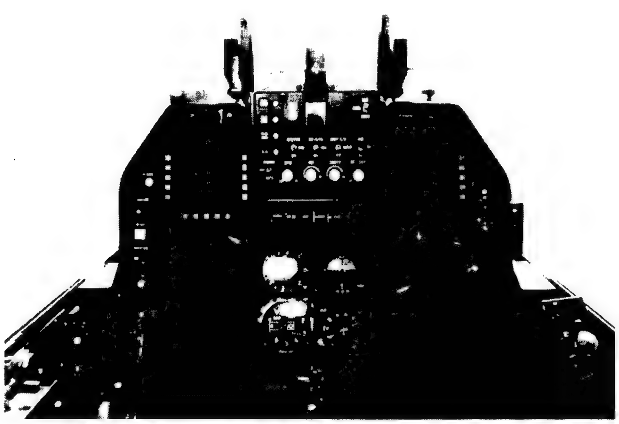
The Hummingbird XV-4B VTOL program produced a wealth of engineering data and influenced the design of subsequent VTOL aircraft.



The AFTI/F-16 flies over a test range at Edwards AFB. Note the target in the background.

The AFTI/F-16 developed, integrated and tested a set of technologies designed to improve the survivability and weapons delivery accuracy of tactical fighters in air-to-air and air-to-ground attacks.

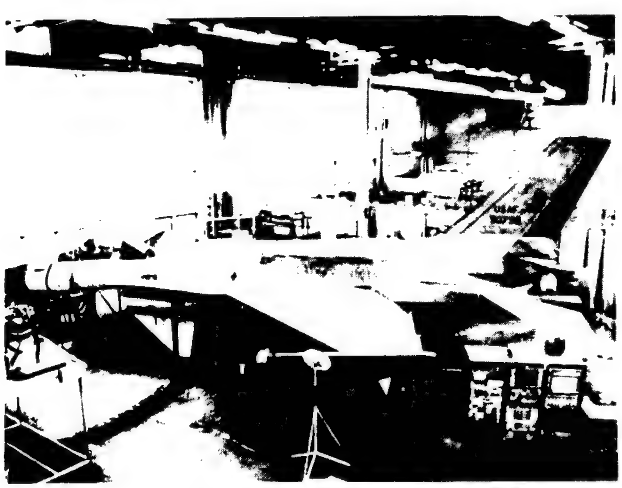
The AFTI/F-16 flight control and direct force features are extensions of the Control Configured Vehicle (CCV) technology developed in the Flight Control Division.



The speed and computational power of the AFTI/F-16's digital computer permits tailoring of flight control laws for specific mission tasks. The pilot communicates with the computer through these cockpit instruments.

concept was the brainchild of Welbourne G. Williams and Charles Cosenza of FDL. The key word is "integration": a number of new technologies would be tested simultaneously, speeding up technology transition and permitting quick development of new fighter aircraft -- and of course, AFTI would save money. Planning for this major undertaking began in 1973 in the Prototype Division with the establishment of the Advanced Fighter Technology Integration ADPO for the selection of an aircraft test bed. The F-16 Fighting Falcon was selected. The Navy and NASA were also partners in the effort. The initial phase was aimed at demonstrating new technologies in subsonic and transonic maneuver, and convergence and tracking capabilities to improve combat effectiveness. The advanced technologies to be integrated into

A curvilinear bombing run developed under the AMAS phase is followed by the AFTI/F-16 during this Close Air Support (CAS) weapon delivery exercise.



Three external features make the AFTI aircraft different from the "average" F-16: the canards by the engine inlet, the dorsal spine between cockpit and tail; and two sensor/designator pods at the junction of wing and body.

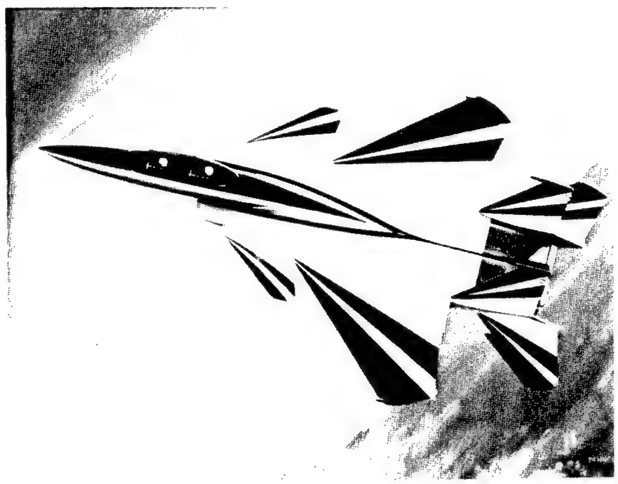
the new fighter aircraft included digital flight control, direct force control and weapon line pointing, integrated flight/fire control, pilot-vehicle interface, variable camber wing, aerodynamic propulsion integration, unique aerodynamic configurations and advanced composite structures. Initial studies were based largely on the fly-by-wire and controlled configured vehicle technologies created at FDL in the 1960s. Three aerodynamic configurations had been considered under the original AFTI program: a variable incidence wing, a jet flap/butterfly canard, and a vectored thrust/supercirculation concept. By 1981 the aircraft had been assembled at General Dynamics/Fort Worth and was ready for flight testing. It incorporated the new digital flight control system, advanced cockpit displays and controls, a highly integrated avionics system, and

new aerodynamic surfaces. One hundred and fifteen test flight hours proved the high reliability of the digital flight control system. Inlet-mounted canards, in tandem with the rudder, produce a side force that enables flat turns. Flap deflections in conjunction with the horizontal tail permit corresponding pitch pointing and vertical translation. In 1982 the aircraft was modified to include the Automated Maneuvering Attack System with its integrated flight/fire control system (IFFC), and then flight tested again. In 1983 a voice command system was successfully used for the first time to change control displays. In July 1984 the AFTI/F-16 program conducted flight test evaluations of the Automated Maneuvering Attack System (AMAS), which integrates decoupled multimode flight control laws with a precise low-altitude air-to-air and air-to-surface attack capability -- the culmination of the Lab's long-term IFFC research. At the same time a Sandia Inertial Terrain Aided Navigation algorithm was tested, demonstrating the reliability of the F-16's digital map. The Air Force Association recognized this program with the prestigious Von Karman Award for outstanding work in science and engineering in 1987.

During the summer of 1988 the AFTI/F-16 participated in testing of new close air support (CAS) technology at Edwards AFB. A digital Automatic Target Handoff System was used to link the F-16 with an Army helicopter, providing enhanced capability to destroy targets without voice communication between the aircraft. The project also permitted further flight testing of other AFTI technology, including the automated digital terrain management and display system, integrated flight/fire controls, an infrared laser sensor tracker, and a helmet-mounted sight.

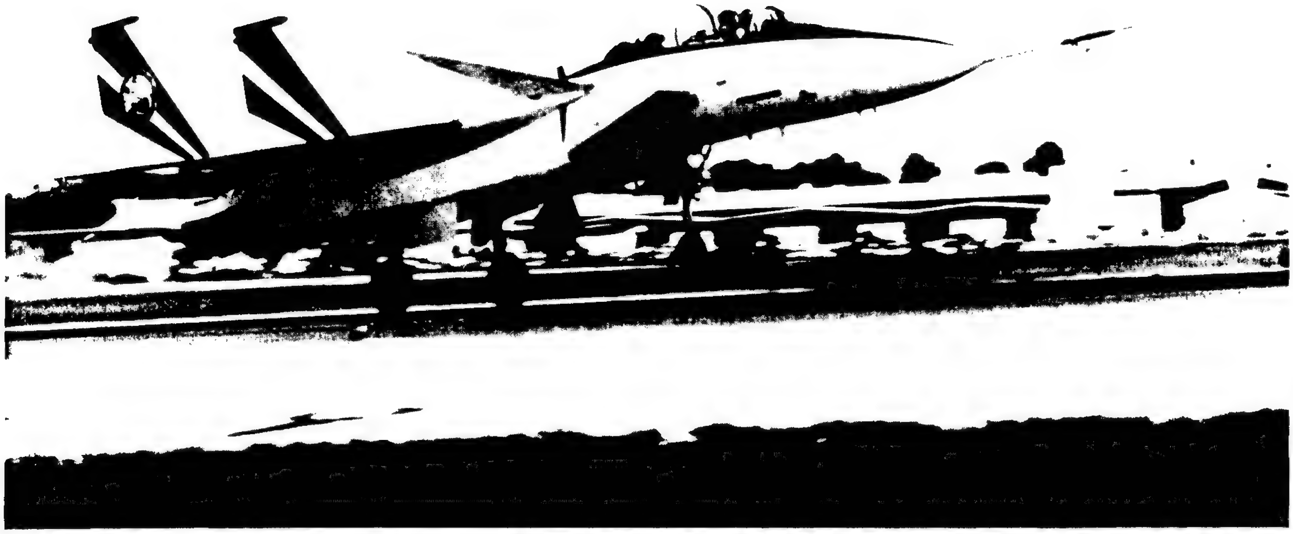
STOL and Maneuvering Technology Demonstrator/F-15

Four new technologies designed to enhance the STOL capability and maneuverability of advanced fighter aircraft were evaluated in the STOL/MTD program, supported by Flight Control Division over a four-year period. A contract was awarded to McDonnell Douglas, which modified an F-15 to demonstrate (1) a two-dimensional thrust vectoring and reversing exhaust nozzle, (2) an integrated flight/propulsion control system, (3) rough/soft field landing gear, and (4) cockpit displays and controllers for STOL operations under night and adverse weather conditions.

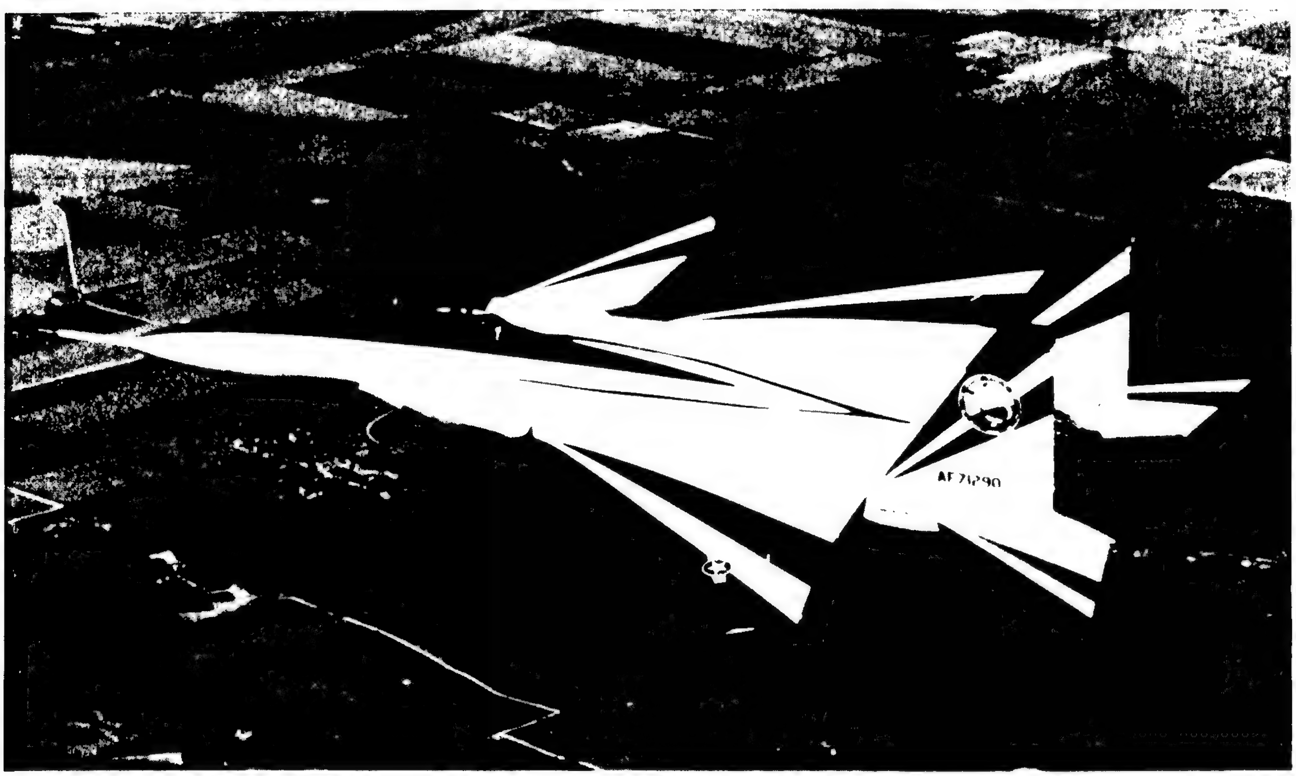


Artist's conception of the F-15 STOL aircraft, showing the canards just ahead of the wing and the two-dimensional thrust-vectoring nozzles.

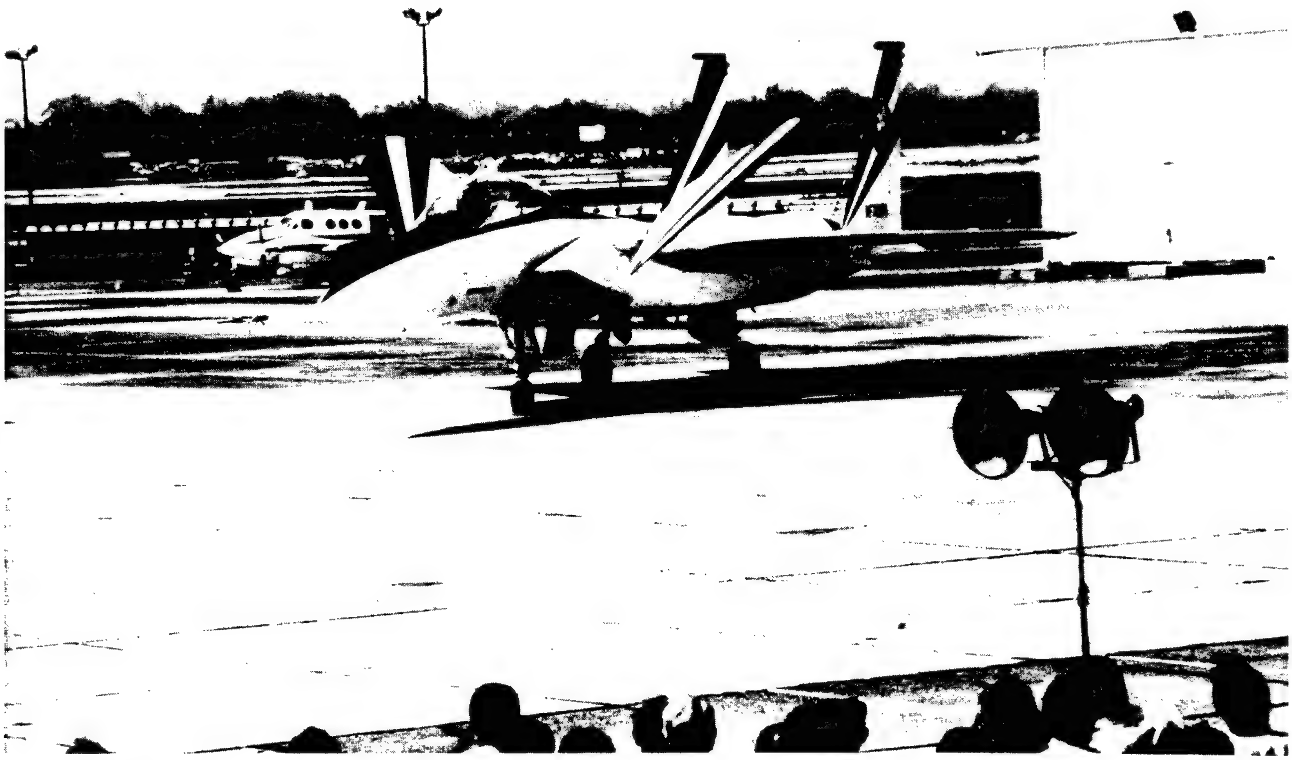
Contracts were let in 1983 for a five-year program. During the first phase components were designed and fabricated; during the second, testing was conducted with the F-15 test bed. Flight testing began in 1988 at the St. Louis facilities of McDonnell Douglas, and was scheduled to continue for thirteen months, the latter phases to take place at Edwards AFB. The most important innovation is the integration of the engines, exhaust nozzles and canards into the aircraft's flight control system. A nonaxisymmetric, two-dimensional nozzle was developed with high thrust reverse and speed brake capability. Two canards placed forward of the wings show promise in enhancing STOL capability for fighter aircraft. The F-15 also incorporates wing panels of aluminum/lithium alloy. The program has been successful and will contribute to future advanced tactical fighters.



The F-15 STOL takes off on its first test flight from Lambert Field in St. Louis.



Phase 1 of the flight test did not include the two-dimensional nozzles. They will be added after full validation of the flight control system and the nozzle-off aerodynamics.

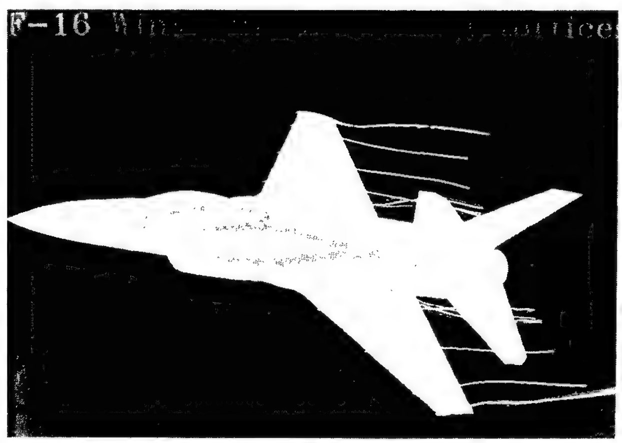


The F-15 STOL's flight control computer has a canned "Ops" routine that checks all control surfaces and aircraft systems to make sure they are functional before takeoff.

Computer Simulation of the F-16A Fighter

The solution of the Navier-Stokes equations continues to pay off in the advancement of computational aerodynamics. The start-to-finish development of an aircraft using only computers is still years away, but in the summer of 1986 the Aeromechanics Division began a project to compute the flowfield about an F-16A fighter. This is a major step toward making design by computer possible.

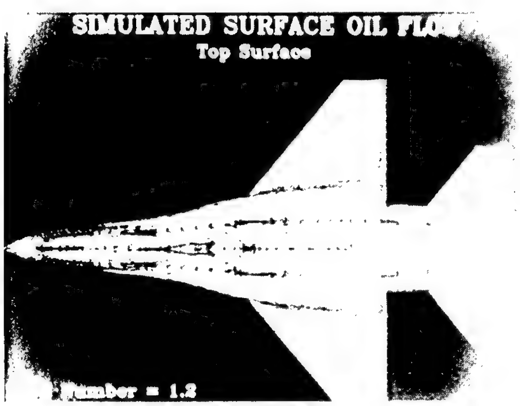
This was the first time a complete, complex aircraft solution was attempted using the Navier-Stokes equations, and Dr. Joseph Shang's FDL3D computer code was chosen for the simulation. This code uses MacCormack's explicit predictor-corrector algorithm to solve the three-dimensional Navier-Stokes equations. FDL3D is a relatively simple code and has been proven accurate over many years by the correct solution of a wide range of supersonic flow fields. The specific case solved was a freestream Mach number of 1.2 and an angle-of-attack of six degrees. These parameters were chosen to correspond to wind tunnel test conditions for comparison purposes.



Computer-generated particle traces show the vortex formation on the strake and from the wingtip of the F-16.

The solution, completed in June 1988, was highly accurate compared to wind tunnel data.

Surface pressure distribution on the F-16A, calculated with the Navier-Stokes equations. Pink indicates high pressure, blue indicates lower pressure.



Simulated surface oil flow generated by the computer. Pictures like this help engineers understand how the wings and body interact in the flow field.

For instance, the wind tunnel coefficient of lift differed by only five percent from the computer coefficient. The computer simulation shows all the major features of the flowfield, including the high pressure caused by the shock waves at the nose and canopy, and the low pressure on top the wings. Accurate flowfield "pictures" are difficult to obtain in a wind tunnel, giving the computer model a clear advantage. The F-16A simulation has demonstrated that complete flow field solutions are possible using computers.

Glossary

ablation/ablative: the erosion of material on a nose cone during atmospheric re-entry.

acoustics: the study of sound and its effect on structures.

active landing gear: the active adjustment of the mechanical and hydraulic components of landing gear to minimize dynamic loads.

active flutter suppression: the use of active devices to control flutter of airframe components.

actuators: a mechanism to activate control surfaces by pneumatic, hydraulic or electronic signals.

adiabatic: refers to thermodynamic change in a system without heat transfer across the system's boundary.

aero-configured missiles: missiles having aerodynamic features to increase their range and/or accuracy, as opposed to ballistic missiles.

aerodynamic decelerators: devices to slow the speed of a landing aircraft or a falling body; most commonly, parachutes.

Air Cushion Landing Gear: a landing system using air under constrained pressure rather than wheels; analogous to a hydrofoil.

angle of attack (AOA): the angle between the wing chord (or other reference axis) and the direction of air flow.

atmosphere (or Environmental) control: the control of air quality and temperature inside the crew area of an aircraft.

autopilots: mechanical or electronic devices which stabilize the attitude of an aircraft around its pitch, roll and yaw axes, with or without some pilot intervention.

avionics: general term for the electronic components of an aircraft, especially its radio and radar.

ballute: a combination balloon/parachute, used to slow the free fall of rockets and missiles.

bearings: a mechanical part which supports another part that slides, rotates or oscillates on it. Essential to wheels, gyros and engines.

bird impact: the damage of aircraft transparencies by collisions with birds. At high speeds a bird impact can cripple or destroy an aircraft.

Boost Glide Re-entry Vehicle (BGRV): an aerodynamic lifting vehicle which is propelled to a high altitude by jets or rockets, and then glides back to earth with little or no propulsion.

Boundary layer control: reducing the friction or turbulence of air as it flows over aircraft wings or bodies, by the choice of proper contours or active sections. Good boundary layer control increases speed, range and fuel efficiency, as well as safety.

boundary layer: the airflow which comes into direct contact with a wing or fuselage surface during flight.

buzz: sustained rapid oscillation of an aerodynamic control surface caused by intermittent flow separation or by shock waves, or by a combination of the two. Buzz phenomenon was a serious problem with missile nose tips before the solution of the Navier-Stokes equations.

camber: the curvature of an airfoil surface mean chord line.

closed-loop environmental control system: a self-contained environmental system which recirculates conditioned air essentially independent of the environment outside the aircraft or spacecraft.

collimation: directing electrons or photons into parallel beams, as in a laser.

Computer-Aided Design (CAD): a method of designing new aircraft or components with the aid of a computer, saving much of the time and expense of building actual models.

Control Configured Vehicle (CCV): an aircraft using aerodynamic controls and automatic flight control systems to supplement natural stability or allow some static instability. CCVs are more maneuverable and less responsive to gusts and structural stress.

control system: any mechanism or electronic system used to control any aspect of an aircraft's operation.

control displays: the gauges, meters, digital or pictorial displays that convey necessary data to an aircraft pilot.

crew escape: techniques allowing the crew to leave the aircraft quickly in case of emergency, including parachutes, ejection seats, etc.

crew stations: the positions or seats occupied by various aircraft crew members, including attendant equipment.

cryogenic cooler: a device used to cool high-temperature components, such as lasers, using a liquid which boils at very low temperatures, such as helium, nitrogen or oxygen.

damage tolerance (crack growth): the amount of cracking or damage that a structure can sustain before it breaks or becomes unsafe.

dampers: a device for minimizing vibration in a component; for example, soundproof materials to prevent acoustic damage.

deployable plastic foam: a foam that can be used on a runway to diminish damage to a landing aircraft, when the landing gear is not functioning properly.

digital flight control: aircraft flight control using digital computer technology.

doublet-lattice subsonic method: a method for predicting subsonic unsteady flows by solving the linearized equations by finite-element methods.

drag: the force retarding the forward motion of an aircraft through the flow field; aerodynamic resistance.

drift indicator: device that records the amount of deviation from an aircraft's course, though not the direction of deviation.

dynamic Loads: loads caused by the acceleration of an aircraft or rocket, or by gusts, manuevering, landing, or the firing of weapons. SEE static loads.

electroluminescent panels: cockpit display panels producing light by means of a phosphor material between sheet-metal electrodes, activated by electric currents passing through the electrodes.

external stores carriage: the attachment of fuel tanks, weapons, etc. to the exterior of an airframe, particularly on the wings. Such carriage has significant effects on the aircraft's aerodynamics and flutter.

feedback: the return of a portion of a circuit's output to its input. The purpose is to "tell" the circuit how far it is from a desired quantity, so that the circuit can adjust more closely to that quantity.

fiber optics: the use of flexible glass or plastic fibers to transmit light signals, which can be modulated like electrical signals to carry information. Their chief advantage over electrical wiring is that they are not affected by outside electrical interference, such as radio waves or lightning.

flight envelope: the boundaries within which an aircraft must operate, defined by such parameters as altitude, range, maneuvers or speed.

flight instrumentation: the instruments used by the pilot to fly the aircraft, such as indicators of speed, trajectory and attitude.

flutter: an aeroelastic, instability caused by the interaction of the airstream with an aircraft structure.

fly-by-light: the use of fiber optics to transmit data in a flight control system.

fly-by-wire: the use of electric circuits to transmit data in a flight control system. Older aircraft used mechanical cables to manipulate control surfaces.

Fowler flaps: a split flap that moves first rearward, then downward along tracks. The purpose is to alter lift and drag on takeoff and landing.

frameless aircraft transparencies: a type of injection molded windshield or canopy that requires no frame and thus has lower weight and higher visibility.

gyro or gyroscope: an instrument that maintains an angular reference direction by use of a rapidly spinning wheel or other mass. Because of its tendency to restore its own equilibrium when disturbed, the gyro is essential for flight stability and control systems.

heat sink: any material (liquid, solid or gas) which can be used to absorb heat.

heat transfer: the absorption of heat from one material or fluid into another. Essential for cooling many aircraft components.

heat exchangers: a device that transfers heat from one medium to another or to the environment, thus reducing the temperature of engines or other components. The automobile radiator is a familiar example.

HiMAT vehicle: Highly maneuverable aircraft technology (a type of research aircraft).

hot-gas control systems: a control mechanism that uses heated gases (rather than hydraulic fluids) to transmit force from the pilot controls to the control devices.

human factors: the study of the limits and capablities of human beings in relation to the design of cockpits, controls, weapon systems, etc.

hush house: a soundproof chamber used to minimize acoustic effects to the outside environment.

hydraulic servoactuator: a servomechanical control device using a fluid to transmit motion.

hypersonic glide vehicle: an aerospace vehicle lifted into the upper atmosphere or into orbit by jets or rockets, which returns to the earth's surface by coasting or gliding.

hypersonic aerodynamics: the study of aerodynamic effects at speeds higher than about Mach 5.

IFFC: Integrated Flight/Fire Control.

inlet design aerodynamics: the study of aerodynamic affects around jet engine inlets.

Integrated Fire/Flight Control (IFFC): the combination of flight controls and weapon-firing controls into the same integrated system; saves space, weight and costs.

Kevlar: a high strength Aramid fiber-reinforced composite material, made by DuPont; similar to fiberglass.

Krueger flap: a leading edge flap forming part of the under surface of a high-speed wing, hinged to swing down and forward to produce bluff leading edge.

lift: the total lifting force perpendicular to the flight path which supports an aircraft in the air.

lift curve slope: the inclination of a lift curve versus angle-of-attack.

lifting body: an aerodynamic design characterized by broad wings and a flat bottom, allowing high aerodynamic lift; for example, the space shuttle.

light-emitting diodes (LED): semiconductor diodes that convert electrical energy into light, familiar in pocket calculators and digital clocks; used in cockpit displays.

Lightweight Fighter: the Air Force explored the LWF concept between 1972 and 1975, but the optimal weight was never defined.

Machmeter: an instrument that indicates the Mach number (velocity of the aircraft relative to the speed of sound).

Micro-Vision: an all-weather landing system developed by Bendix, using pulsed beacons along the runway to activate a pattern on the pilot's heads-up display.

Mission Adaptive Wing (MAW): an advanced composite wing whose configuration can be altered for different types of mission.

Moderate STOL: a variety of short take-off and landing vehicle that uses some horizontal motion, like a conventional aircraft.

monocoque: a fuselage in which all the strength is in the skin and its underlying framework, with no interior bracing. Developed in the 1930s, metal monocoque technology was the first major advance over wooden airframes.

multi-ship integration: the control of more than one aircraft or weapon system by a single integrated control system, to allow for greater efficiency and accuracy.

Navier-Stokes equations: the equations for the motion of a viscous fluid (such as air or water) over a surface. The numerical solution of these complex equations makes it possible to understand and control many aspects of fluid dynamics.

nucleonics: science of applying nucleons and other atomic emissions.

OMS pod: "orbital maneuvering system" pod, a structure near the rear of the space shuttle, whose configuration was improved by Lab scientists.

panel flutter: the aeroelastic instability or 'flutter' of aircraft body panels, as opposed to wing flutter.

parasol wing: a type of wing from which the rest of the aircraft is suspended by ties.

Pictorial Display Format: a cockpit display showing graphic 'pictures' on a screen, like television, rather than data in the form of numbers. Greatly improves pilot efficiency and reaction time.

piston theory: an approximate method of predicting unsteady aerodynamic forces at hypersonic speeds.

Profilograph: a device developed at the Lab to measure the roughness or contours of a runway or other landing surface, for the purpose of improving the design of landing gear.

Project Paperclip: the program which recruited German scientists and brought them into American military labs after World War II.

radar cross-section: the degree to which an aircraft or missile is visible to radar; the lower the cross-section, the more difficult the vehicle is to detect.

radiative/radiation cooling: cooling by direct radiation from the surface, rather than by heat exchange.

radome: the protective dome or other covering over a radar antenna or other aerial.

redundancy: the use of several identical channels to transmit data, as insurance in case one or more channels fail.

Remotely Piloted Vehicles: small pilotless drones, used for reconnaissance or weapons, directed by radio control.

scramjet: supersonic combustion ramjet, a modified ramjet used to propel vehicles at hypersonic speeds.

sensors: a devices which senses absolute values or changes of temperature, flow rate, pressure, etc., and transmits the data to a computer or the pilot.

separated flow: airflow which is no longer 'attached' to the moving aircraft; can cause turbulence.

solid state displays: cockpit displays utilizing transistors or diodes rather than vacuum tubes.

sonic fatigue: failure or cracking of a structure due to stress produced by sound waves.

stability: the quality of an aircraft which resists disturbances and/or causes the aircraft to return to a stable condition after a disturbance. Airplanes cannot fly without stability.

stability augmentation: subsystems of a flight control system which use various kinds of feedback to improve stability.

stall/spin: the uncontrolled rotation of an aircraft about its axis after an engine stall, often resulting in loss of the vehicle. A flight-control problem.

static loads: loads on an aircraft not resulting from its dynamic motion; the pressure exerted by the weight of the vehicle and its components.

static testing: structural testing of a non-moving vehicle, to verify structural design criteria, integrity, and the effects of loads, or to measure engine thrust.

stringer: longitudinal structural member in an aircraft fuselage or wing, providing the essential 'skeleton' of the aircraft.

structural Loads: stresses applied to an airframe by the weight and shape of the aircraft itself, as well as by flight conditions.

subsonic aerodynamics: the study of aerodynamic effects at speeds lower than Mach 1 (the speed of sound).

supercritical airfoils: wings designed to minimize shock waves and drag, required for high speed and performance.

supersonic aerodynamics: the study of aerodynamics at speeds above Mach 1, up to about Mach 5.

survivability: the capability of an aircraft structure to avoid and/or sustain stresses and damage from the environment without losing the ability to perform its mission, or without danger to the pilot and crew.

Technology Assessment: a function of the FDL involving the evaluation of new and advanced technologies before the Lab commits heavily to those technologies.

Tee: an arrangment of cockpit instruments and displays in a "T" shape; now standard in most aircraft.

tension pads: devices applied to the wing or airframe during ground testing, to simulate flight loads. The modern successor to the sandbags and shot used by the earliest airplane designers.

thermal control: the control of temperature in an aircraft or one of its subsystems or components.

trajectory analysis: the study of the curve or vector followed by an aircraft or other object moving through space. FDL pioneered in computerized trajectory analysis.

transducer: a device which translates one form of energy into another (for example, mechanical motion into an electrical impulse).

transonic aerodynamics: the study of aerodynamic effects close to Mach 1, involving complex and nonlinear flows as the vehicle "breaks the sound barrier."

variable geometry aircraft: one whose shape can be varied to meet different flight conditions; usually refers to variable wings.

variable geometry inlet: a jet engine inlet whose diameter or direction of flow can be changed, altering the flow path for greater efficiency or to convert the engine into a ramjet.

vibration: a continuing periodic movement of part of an aircraft, resulting in undesirable stresses.

viscoelasticity: the behavior of a material which 'remembers' previous stresses and exhibits viscous and delayed elastic response to stress; important to an understanding of vibration damping.

viscous flow field: the flow of air (or water) around a vehicle as it moves through the fluid; an essential determinant of aerodynamic design.

voice control technology: the activation of controls by the pilot's voice, rather than manually or automatically.

Vuilleumier cycle: a power cycle connected to a refrigeration cycle, each of which has two constant volume and two constant temperature processes.

vulnerability: the inability of an aircraft to withstand the damage caused by a hostile environment.

zero lift: angle of attack at which the airfoil generates no lift.

Zero-reader: an early flight instrument, developed by Sperry. The pilot flew the aircraft by centering two crossed needles (indicating vertical and lateral displacement) on a "zero point."

AFTERWORD

As the Flight Dynamics Laboratory moves toward the twenty-first century, it will continue to lead the world in the development of advanced aircraft and weapons systems. Problems not even imaginable today will be encountered and solved. At present the Lab is playing a major role in the development of the National Aerospace Plane, also known as TAV (trans-atmospheric vehicle). It will continue to evaluate and improve current aircraft systems, with a view to improving safety, survivability and cost effectiveness.

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NOTES

GENERAL:

The essential outline of this book was derived from a series of reports published by FDL over the years under the title *Technical Foundations for Future Aerospace Vehicles and, later, Flight Vehicle Technology for Future Aerospace Vehicles*. Technologies described in this series will not be cited separately in this section, as it contributed to nearly every item. The second most valuable source of information was personal interviews (see bibliography), and written suggestions from various employees of FDL. In some cases their "re-writes" have been incorporated verbatim. A third valuable source was the files of Lt. Paul Rohs of FDL, who began gathering information on the history of the Lab in 1986; these files include work by George Loptein. A sketch of FDL history written by Robert Boots was also most helpful. A pamphlet entitled "Air Force Systems Command Activities [1976] provided basic information on many programs.

CHAPTER ONE:

Information on the early years of military flight, from the Signal Corps through the establishment of Wright Field, is derived primarily from the landmark study by Lois Walker and Shelby Wickam: *From Huffman Prairie to the Moon: The History of Wright-Patterson Air Force Base*, Air Force Logistics Command, WPAFB, 1988. Comparison between Aircraft Lab and industry: p. 94

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Albert E. Misenko and Barton Krawetz, *History of the Aeronautical Systems Division, October 1982-December 1983, Part II: The Air Force Wright Aeronautical Laboratories* (Historical Division, Information Office, ASD (WPAFB) also provided corroborative evidence.

Aside from Walker and Wickham, details on the reorganizations of the Aircraft Lab and the Flight Dynamics Lab came from interviews with C. Ray Bryan, George Yingling, Richard Hoener, Charles Westbrook, William Lamar and others, and from a short paper by David Felker, "Historical Background -- Aircraft Laboratory, August 1907 - October 1959." Especially useful was a paper by Dr. John Allen, "Some Thoughts on Management of In-House Laboratories" (WPAFB, 1974).

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